FINAL REPORT

EFFECT OF VOIDS ON GRAPHITE FIBER REINFORCED COMPOSITES

Contract No. N00019-71-C-0305

by E. F. Olster

AVCO CORPORATION
SYSTEMS DIVISION
Lowell Industrial Park
Lowell, Massachusetts 01851

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Prepared for

U. S. Naval Air Systems Command
Washington, D. C. 20360

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FOREWORD

This report was prepared by AVCO Systems Division, Lowell, Massachusetts 01851, under Department of the Navy Contract N00019-71-C-0305, titled "Effects of Voids on Graphite Fiber Reinforced Composites". This program was administered through the Naval Air Systems Command under the cognizance and direction of Mr. M. Stander. This report describes the work performed between April 1971 and April 1972. The principal investigator for this project was Dr. E. F. Olster.

ABSTRACT

Porosity has been artifically introduced in graphite/epoxy laminates by either varying the volitale content of the prepreg or by altering the pressure during curing. A series of techniques was used to determine the resulting porosity and establish the variability within a panel. These techniques included direct and indirect measures of the void content and were compared to standard non-destructive techniques for porosity detection.

Tensile, compressive, shear and flexure properties were obtained on unidirectional and cross plied specimens. The properties showed varying sensitivity to porosity, the horizontal shear strength being the most severely degraded of those properties measured.

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1.0 INTRODUCTION AND SUMMARY

Porosity has a pronounced effect on the mechanical properties of graphite/epoxy composites. Studies have shown that certain processing variables contribute substantially to porosity. Modmor II/5206 has, within the past few years, emerged as one of the more attractive graphite/epoxy composites and hence it was important that the interrelations between processing, porosity, mechanical properties and quality assurance techniques be investigated. Therefore, the specific objectives of this program were (1) to determine the effects of processing variables, such as changes in volitale content in the resin and changes in molding pressure, on the void content in Modmor II/5206 composites, (2) to obtain definitive data on the effects of porosity on the mechanical properties of unidirectional and cross ply laminates, and (3) to determine the applicability of standard nondestructive, quality assurance tests for the detection of porosity.

Implicit in the objectives is the accurate measurement of porosity. Prior to these efforts researchers have had considerable difficulty in determining with sufficient accuracy the void content in graphite/epoxy composites. Two new techniques, one using computer aided image analyzing equipment and the other using water absorption data were successfully used. As a result it was determined that processing using vacuum bag molding resulted in a void content of approximately 5% whereas standard autoclave molding results in a porosity of approximately 0.5% depending upon the volitale content of the resin. Low volitale content, resulting from 72 hours of artificial air drying, and high volitale content resulting from the addition of 1% by weight MEK to the prepreg produces void contents of 0.25% and 1.125% respectively. These porosity levels were in turn reflected in the mechanical properties which in general decrease as the porosity increases.

The short beam shear strength is the property which is most significantly affected by porosity; compared to void free properties it decreases by 10% for each additional 1% voids. The compressional and flexural properties are also substantially degraded; they suffer a 5% decrease for each 1% increase in porosity. The tensile properties of both unidirectional and cross ply laminates are only slightly degraded by porosity; each 1% increase in the void content results in a 2% decrease in properties. Of the standard nondestructive quality assurance techniques employed here, acoustic attenuation was found to be highly sensitive to porosity whereas acoustic velocity was not sufficiently discriminating in many cases.

Some of the prepreg sheets contained defects such as wavy tows, a whiskered surface or a non-uniform resin coating and it is worthy of mention that these prepreg variations were found to have no effect on the mechanical properties of cured laminates.

2.0 MATERIAL

The composite used for this study was Modmor II/5206 a graphite/epoxy prepreg manufactured by the Whittaker Corporation. The prepreg was ordered in the form of 12" square unidirectionally reinforced sheets; the material characteristics reported by Whittaker for this material are given in Table 2.1.

2.1 Fabrication Technique

In an effort to introduce a varying void content four (4) processing procedures were chosen, namely: vacuum bag molding of normal prepreg; autoclave molding of normal prepreg; autoclave molding of advanced (air dried) prepreg* and autoclave molding of prepreg containing excess solvent**. The cure cycle was the same one recommended by the manufacturer and is 50 minutes at 270°F followed by 2 hours at 350°F. A pressure of 85 psi was used for the autoclave molded laminates whereas the vacuum bag molded laminates were subjected to a pressure of 14 psi. It should be noted that vacuum bag molding is not a typical fabrication technique but was used to obtain a high porosity laminate in order to establish an upper bound on void contents and their effects on mechanical properties.

2.2 Graphite/Epoxy Laminates

2.2.1 Description of Laminates

A brief description of the panels, their size, layup and the type of specimens cut from them is given in Table 2.2. The 12 panels comprising Group I were used for the basic study of the effect of voids on the mechanical properties. The four panels in Group II were used to determine the effect of the observed prepreg variations on the mechanical properties. Finally, the two panels in Group III were used to determine whether or not this composite would, after being immersed in boiling water, regain its virgin properties at room temperature.

This last series of tests was prompted by the use of water absorption data to determine porosity.

2.2.2 Laminate Quality

2.2.2.1 Nondestructive C-scan Evaluation

A C-scan was taken of each panel in order to assess its overall quality and its uniformity. The setup permitted a measurement of the variations in acoustic attenuation through the thickness of the composite. In general high attenuation is caused by porosity or by surface defects. The results are summarized in Table 2.3. The general porosity level was established by the total acoustic energy required to accurate the receiver. As can be seen the vacuum bag molded panels have high porosity whereas all others have a low porosity. The uniformity was established by observing variations in both a high and low sensitivity C-scan.

---

*The prepreg was allowed to air dry for 72 hours at RT prior to molding.
**1% (by weight) MEK was added prior to molding.

TABLE 2.1

CHARACTERISTICS OF THE GRAPHITE/EPOXY PREPREG

1. Material - Modmor II/5206
2. Batch No. 93
3. Manufacturing Date - 5/12/71
4. Physical Properties of Prepreg

Reinforcement	
Tensile Strength (minimum)	350,000 psi
Tensile Modulus (minimum)	35×10^6 psi
Specific Gravity, gram/cc	1.74 ± 0.05
Filament Diameter, microns	8.1 ± 0.5
Filaments per Tow	10,000
Resin Content, %	42 ± 3
Tows per inch, nominal	5-1/2
Thickness, per ply, nominal, inches	
"B" Stage	.0095
Cured	.008
Shelf Life	Ninety days from date of shipment when stored at 0°F in sealed containers.

5. Mechanical Properties - Unidirectional Material having a nominal fiber volume fraction of 64%

Property	Test Temp $^{\circ}$F	
0° Tensile Strength	RT	200 KSI
	350	190 KSI
0° Tensile Modulus	RT	22×10^6 psi
	350	20×10^6 psi

TABLE 2.1 CONTINUED

0° Compressive Strength	RT	160 KSI
	350	123 KSI
0° Flexural Strength	RT	250 KSI
	275	220 KSI
	350	95 KSI
0° Flexural Modulus	RT	21×10^6 psi
	275	19×10^6 psi
	350	16×10^6 psi
0° Short Beam Shear	RT	16 KSI
	300	9 KSI
	350	8 KSI
90° Flexural Strength	RT	17 KSI
	300	7 KSI
90° Tensile Strength	RT	8 KSI

TABLE ..2

PANEL DISPOSITION

Avco Log Book	Group**	Number of Plys	Size Inches	Fiber Orientation	Fabrication Technique	Number of Specimens: Tension LT	Tension TT	Tension 45°T	Flexure LF	Flexure TF	Horiz Shear	Long Comp.	Void Char	Notes Prepreg Quality
1109-38	I	7	12 x 12	0/90/0/90/0/90/0	VB*	6	6	6	--	--	- - -	- -	8	Normal
1109-41	I	7	12 x 12	0/90/0/90/0/90/0	AC*	6	6	6	--	--	- - -	- -	8	Normal
1109-55	I	7	12 x 12	0/90/0/90/0/90/0	ES/AC*	6	6	6	--	--	- - -	- -	8	Normal
1109-58	I	7	12 x 12	0/90/0/90/0/90/0	AP/AC*	6	6	6	--	--	- - -	- -	8	Normal
1109-36	I	12	6 x 12	0°	VB	-	-	-	10	6	30	16	3	Normal
1109-39	I	12	6 x 12	0°	AC	-	-	-	10	6	30	16	3	Normal
1109-54	I	12	6 x 12	0°	ES/AC	-	-	-	10	6	30	16	3	Normal
1109-57	I	12	6 x 12	0	AP/AC	-	-	-	10	6	30	16	3	Normal
1109-37	I	6	6 x 12	0°	VB	10	6	-	--	--	- - -	- -	8	Normal
1109-40	I	6	6 x 12	0°	AC	10	6	-	--	--	- - -	- -	8	Normal
1109-53	I	6	6 x 12	0°	ES/AC	10	6	-	--	--	- - -	- -	8	Normal
1109-56	I	6	6 x 12	0°	AP/AC	10	6	-	--	--	- - -	- -	8	Normal
1109-63	II	6	6 x 12	0°	AC	10	6	-	--	--	- - -	- -	-	Dry
1109-64	II	6	6 x 12	0°	AC	10	6	-	--	--	- - -	- -	-	Wavy
1109-65	II	6	6 x 12	0°	AC	10	6	-	--	--	- - -	- -	-	Fuzzy
1109-66	II	6	6 x 12	0°	AC	10	6	-	--	--	- - -	- -	-	Normal
1109-59	III	12	12 x 12	0°	AC	-	-	-	15	16	30	30	-	Normal
1109-62	III	12	12 x 12	0°	AC	-	-	-	15	16	30	30	-	Normal

* VB - Vacuum Bag, AC - Autoclave, ES - Excess Solvent, AP - Advanced Prepreg

** Group I — Will allow as assessment of effect of fabrication technique on porosity and its effect on mechanical properties.
Group II — This group used to find effect of prepreg quality on mechanical property variations.
Group III — Half of specimens from these panels water boiled and dried - compare to virgin specimens - determine the effect of this cycle on mechanical properties.

LT - Longitudinal Tension, TT - Transverse Tension, LF - Longitudinal Flexure, TF - Transverse Flexure

TABLE 2.3

SUMMARY OF C-SCAN EVALUATION

Panel	Molding* Technique	Groups	Porosity	Uniformity	Key
1109-38 1109-41 1109-55 1109-58	VB AC AC/ES AC/AP	I I I I	High Low Low Low	Poor Good Good Excellent	Excellent - no apparent variability.
1109-36 1109-39 1109-54 1109-57	VB AC AC/ES AC/AP	I I I I	High Low Low Low	Poor Fair Poor Good	Good - slight variability, some regions of moderate attenuation.
1109-37 1109-40 1109-53 1109-56	VB AC AC/ES AC/AP	I I I I	High Low Low Low	Poor Good Fair Excellent	Fair - substantial variability - some regions of high attenuation.
1109-63 1109-64 1109-65 1109-66	AC AC AC AC	II II II II	Low Low Low Low	Good Good Good Good	Poor - extreme variability - numerous and significantly large regions of high attenuation.
1109-59 1109-62	AC AC	III III	Low Low	Excellent Excellent	

*VB = Vacuum Bag
AC = Autoclave
AC/ES = Autoclave Molding of Prepreg with Excess Solvent
AC/AP = Autoclave Molding of Advanced (Air Dried) Prepreg

The vacuum bag molded panels have greater variability than do the autoclaved laminates. However, one autoclaved molded panel (1109-39) has a significant amount of variability which, as will become evident later, is reflected in the porosity data and mechanical properties.

The C-scan data on panel 1109-54 suggests that this laminate has an extreme amount of variability. Some of this was due to surface imperfections and does not reflect the internal structure of the composite. This was the only panel, however, which was found to have a significant amount of surface defects (See Figure 2.1).

2.2.2.2 Effects of Prepreg Variations on Laminate Quality

Most of the prepreg obtained from Whittaker under this contract was uniform in appearance. Certain sheets however contained defects such as wavy tows, (Figure 2.2), a whiskered or fuzzy surface, (Figure 2.3) or a non-uniform distribution of resin. It was felt that these variations in prepreg quality might affect the porosity and mechanical properties, in effect introduce a scatter band too wide to allow an accurate assessment of the property changes due to the variations in the fabricating techniques (vacuum bag, autoclave, etc.). In order to investigate this, three 6 ply unidirectionally reinforced test panels were fabricated using the wavy, whiskered, and fuzzy prepreg and compared to a fourth panel made using standard quality prepreg.

Ten longitudinal and six transverse tensile specimens were cut from each of the four panels. The specimens were straight sided and had fiberglass tabs bonded to distribute the gripping loads. The test data is located in Appendix A and is summarized in Table 2.4. As is evident from the data the material exhibits some variability. For example, the longitudinal properties from any given panel have a coefficient of variation in the order to 12% for strength, 10% for failure strain, and 5% for modulus. The transverse properties show similar property variations but are only one half the magnitude. Applying statistical techniques it can be shown that, within 95% confidence limits, the effects of the prepreg variations are negligible. The only exception was the transverse tensile strength of resin starved prepreg. However, since this type of prepreg defect was the least common and occurred in insignificant amounts we conclude that the three prepreg have no significant effects on the mechanical properties observed. This statement refers to the quantity, distribution and severity of defects in the prepreg used in this study and must not be generalized or used out of context. This series of tests demonstrated that the effects were not too numerous nor too frequent to affect the mechanical properties and therefore no restrictions need to be placed on the data to be discussed subsequently.

NOTE THAT THE HIG.: ATTENUATION AREAS CORRESPOND
IN GREAT PART TO THE SURFACE IMPERFECTIONS (RIGHT)

Figure 2.1 C-SCAN OF PANEL 1109-54 (LEFT) AND PHOTO OF THE PANEL'S SURFACE FEATURES (RIGHT)

Figure 2.2 EXAMPLES OF WAVY TOWS IN MODMOR II/5206

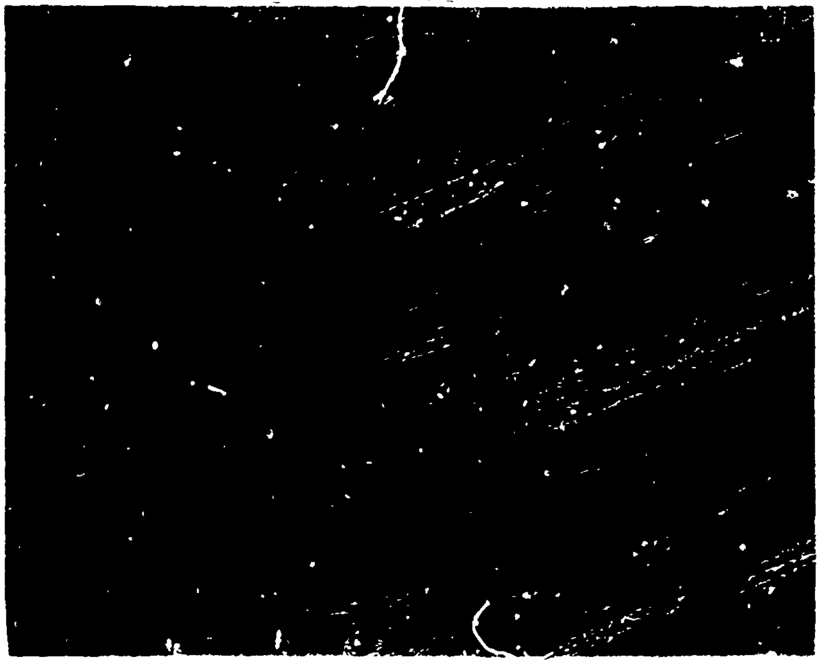


Figure 2.3 CLOSEUP OF THE WHISKERED SURFACE OF SOME MODMOR II/5206 PREPREG

TABLE [illegible].4

TENSILE PROPERTY VARIATIONS AS A FUNCTION OF PREPREG QUALITY

Type of Test	Material	Panel	Prepreg Appearance	Property						Number of Specimen
				Strength		Modulus		Strain		
				$\bar{X}$	Cv	$\bar{X}$	Cv	$\bar{X}$	Cv	
				psi	(%)	($x10^6$ psi)	(%)	(%)	(%)	
LT	6 Ply UD	1109-66	Standard	146,000	14.0	18.9	1.0	.75	13.4	10
		1109-63	Dry	157,000	12.4	18.4	1.0	.83	11.6	10
		1109-64	Wavy	164,000	14.4	19.5	4.9	.81	11.0	10
		1109-65	Fuzzy	149,000	11.2	18.9	5.3	.78	7.5	10
TT	6 Ply UD	1109-66	Standard	5910	7.2	1.31	3.1	.45	6.2	6
		1109-63	Dry	5190	10.4	1.20	1.7	.44	10.1	6
		1109-64	Wavy	5760	5.2	1.25	2.4	.46	5.7	6
		1109-65	Fuzzy	5810	1.2	1.16	3.8	.49	11.8	6

Note:

1. All specimens were autoclave molded

Overall Average

	Strength (psi)	Modulus ($x10^6$ psi)	Strain (%)
Longitudinal	154,000	18.9	.79
Transverse	5,667	1.23	.46

3.0 VOID CHARACTERIZATION

3.1 Investigation of Techniques

3.1.1 Introduction

The C-scan data indicated that certain panels, generally the vacuum bag molded ones, exhibit large variations in porosity. These variations occur over small distances (in the order of 1") and therefore the quantitative techniques used to characterize porosity should be sufficiently sensitive to detect these variations. Prior work by Shultz (Reference 1) indicated that the expected porosity for Modmor II/5206 fabricated using the four molding techniques described earlier is in the range of 0 to 4%. The methods therefore must clearly be able to discern porosity to at least 1% to have any applicability in this study. Further, techniques which are nondestructive are most desirable since once the relationships between porosity and mechanical properties are known they can be incorporated into acceptance criteria.

In order to evaluate the various methods proposed for determining the void content, a portion of an autoclaved, 8 ply unidirectional Modmor II/5206 laminate was used. The specimens were subjected to a metallographic point count analysis which served as a reference technique. Portions of the same specimen were then evaluated using a water absorption technique and using conventional density techniques.

3.1.2 Metallography

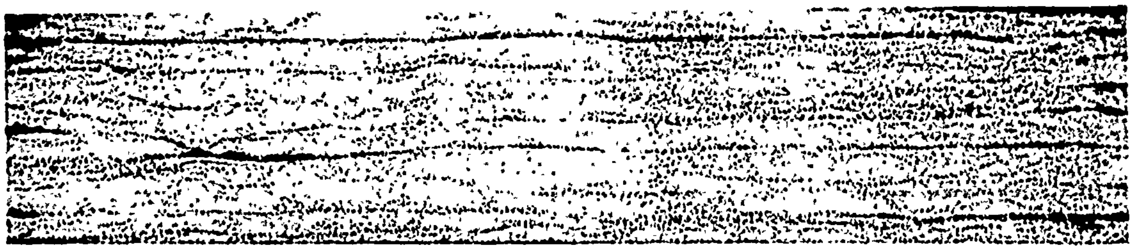
The so called metallographic point count technique superimposes a fine grid over a picture. The measurement is based upon the number of grid intersections overlying regions of interest, in this case, voids. Semi-automatic image analyzing computers perform this task quickly and efficiently. IMANCO,* the developers of the Quantimet analyzer, performed this task and have provided porosity levels, the number of distinct voids, and the distribution of the length of voids throughout the specimen. They performed this analysis on 10x photomicrographs which we supplied. The grid contained 160 lines per inch which is equivalent to 1600 lines per inch of the actual specimen.

Metallographic work performed by Lenoe (Reference 2) showed that voids in Modmor II/5206 epoxy were primarily cigar shaped and orientated so that their principal axis coincided with the filament direction. Identical results were found in this study. The length of the void was much larger than its width or thickness and hence approaches a cylindrical void. As a result, the area fraction determined from cross sections cut perpendicular to the fiber axis is equivalent to the volume fraction of voids.

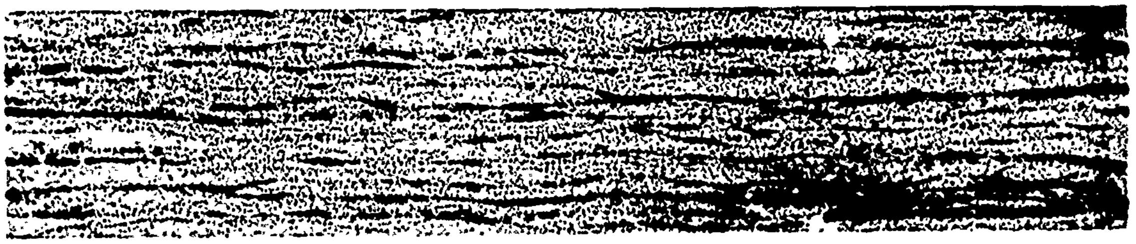
For the preliminary tests four specimens were examined. Micrographs are shown in Figure 3.1. Two of these containing the greatest porosity (No. 2 and 3) were sent to IMANCO for a porosity analysis and were found to have a porosity of 2.72% and 1.75% respectively. This technique, although destructive and fairly expensive, is accurate and highly reproducible.

---

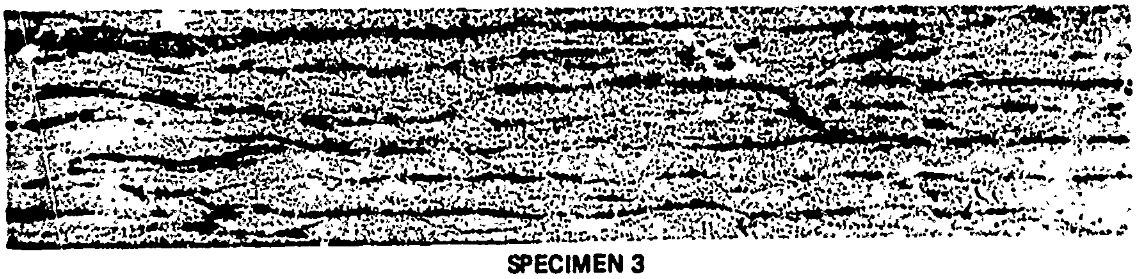
*Image Analyzing Computer, Inc., Monsey, New York.



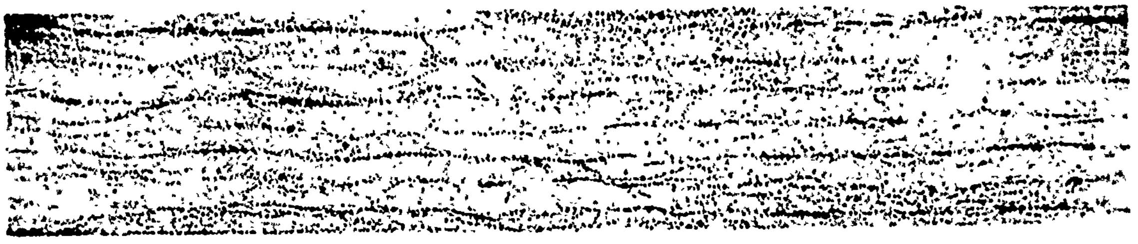
SPECIMEN 1



SPECIMEN 2



SPECIMEN 3



SPECIMEN 4

Figure 3.1 PHOTOMICROGRAPHS OF MODMOR II/5206 LAMINATES

3.1.3 Standard Density Techniques

In a prior study Lenoe (Reference 2) showed that 0.10% variation in the following: the resin density, the fiber density, the composite bulk density, and the volume fraction, would result in an apparent porosity variation as great as 2 4%. This is the order of the porosity variation expected using the processing techniques employed here. Therefore, extremely accurate measurements must be made in order to observe the expected porosity variations. Measurements become more accurate as the size of the specimen increases; however, as the C-scan records imply there are variations within each panel. These variations should be detected rather than averaged and therefore the specimen sizes should not be greater than 1" x 1".

The standard density techniques compute the porosity according to the relation:

$$P = \frac{1}{BD} - \frac{W_r}{\rho_r} - \frac{W_f}{\rho_f}$$

where: P = total porosity
BD = bulk density of the composite
W = weight fraction
ρ = density

Subscripts r = resin, f = fiber

In order to determine porosity from density measurements, it is necessary to know the density and the weight fraction or volume fraction of each component. Lenoe (Reference 2 and 3) used a resin burnoff technique with Thornel 50/epoxy composites. This method in which the specimen is heated in air (oxidized) while continuously recording the weight loss is referred to as a thermogravimetric analysis (TGA). Modmor II fibers were found to be relatively stable at 400°C and therefore a Modmor II/5206 composite was then tested (isothermally) at this temperature. As shown in Figure 3.2 most of the resin burns off rapidly. The curve then continues to drop slowly indicating that the fibers are gradually oxidizing. The approximate weight fractions (From Figure 3.2) can be seen to be 77% fibers and 23% resin. However, because a resin residue might remain and because it is not known precisely at what point no fiber oxidation has occurred, these weight fractions must be considered as approximations. It should be pointed out that the density of the resin cannot be determined from the composite samples. The manufacturer quotes the resin density as 1.25 g/cc and from discussions with knowledgeable personnel at Avco (Reference 4 and 5) this is expected to be relatively invariant property. The fiber density, determined by displacing kerosene, was found to range from 1.770 to 1.779 with an average of 1.775 g/cc. Bulk densities on portions of samples 1 to 4 were determined using weights and volumes determined by direct measurement. These densities are listed in Table 3.1. Using the following approximate data:

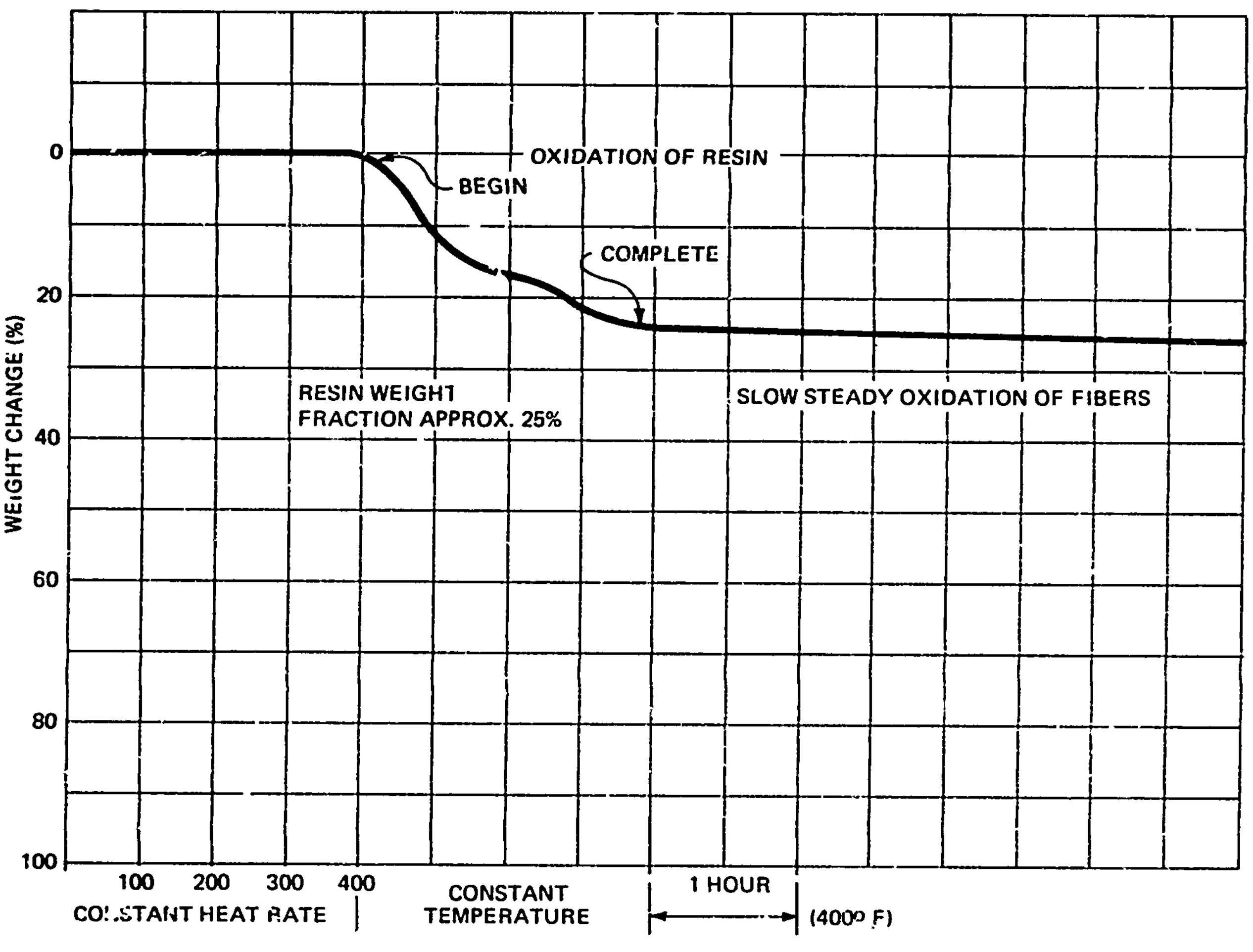


Figure 3.2 TGA FOR MODMOR II/5206

	Density	Weight Fraction
Fiber	1.775 g/cc	77%
Resin	1.25 g/cc	23%

Porosity calculations were made which are given in Table 3.2. The agreement with the metallographic data is poor and is attributed to inaccuracies inherent in the method as discussed in detail by Lenoe (Reference 2).

It is obvious that there are several disadvantages of this method, namely:

1. The density of the resin cannot be determined from individual specimens.
2. It may not be possible to determine the weight fractions accurately enough.
3. Due to wetting problems it is difficult to measure the density of the fibers accurately.
4. It is difficult to attain the accuracies required for reproducible porosity calculations.

In view of the disadvantages of this technique for porosity calculations, it was felt that the emphasis should be placed upon other methods.

3.1.4 Water Absorption

The preliminary results of some in-house research (Reference 6) and subsequently a search of the literature (Reference 7, 8, 9, 10, 11, and 12) suggested that water absorption might be a suitable technique for porosity determination. By the process of diffusion, a void free sample of resin will absorb water. It has been shown (Reference 6, 9, 10, and 12) that the rate of absorption is dependent upon pressure and temperature. Under fixed conditions, for example boiling water, the resin will reach some equilibrium condition where no additional water will be absorbed. A sample of the same resin containing closed pores under identical conditions will absorb moisture more rapidly (Reference 10 and 12) and reach a different equilibrium condition where the resin is "saturated" and the voids are full of water. By subtracting the absorption due to the resin alone the weight of water in the voids can be calculated. The details will be elucidated in a moment. What is of great value is the fact that not only is this method accurate but as will be shown subsequently it can be used prior to mechanical testing (providing that the specimens be fully dried), thus eliminating the hazzard that cracks formed during mechanical testing will be mistaken for porosity.

The application to a composite is as follows: The water absorption characteristics of the resin are given in Figure 3.3. A typical composite has 25% by weight of resin. The weight gain of a void free composite is therefore 25% of that obtained from the resin sample (See Figure 3.3). A composite containing porosity will pickup additional moisture to fill the voids as shown by the dotted lines in Figure 3.3; this excess moisture is directly related to porosity. The composites weight 1.5 g/cc; water weights 1 g/cc; each of 1% of excess moisture is roughly a .015 g/cc increase in density which therefore corresponds to a 1.5% volume of water, hence a 1.5% porosity.

TABLE 3.1

BULK DENSITY OF MODMOR II/5206 SPECIMENS

Specimen	Bulk Density
1	1.567
2	1.524
3	1.533
4	1.630

TABLE 3.2

POROSITY MEASUREMENT TECHNIQUES, DENSITY VERSUS METALLOGRAPHY

Specimen	From Density Porosity (%)	From Metallography Porosity (%)
1	1.1	*
2	2.9	2.72
3	2.5	1.75
4	-1.4	*

*Not Determined

Note: The cross sections of these specimens are given in Figure 3.1.

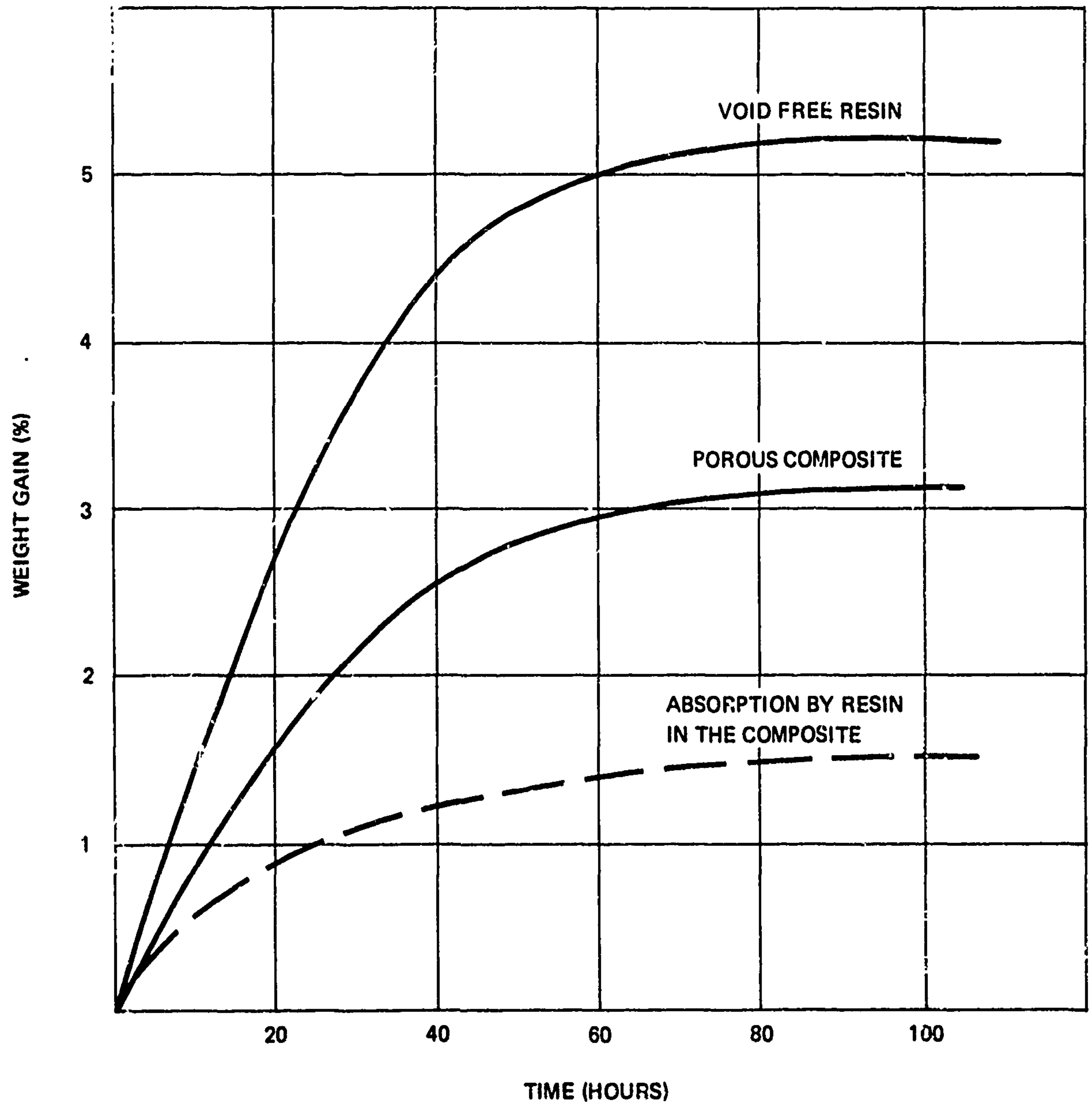


Figure 3.3 SCHEMATIC OF WATER ABSORPTION BY MODMOR II/5206

Several experiments were performed to verify the applicability of the water absorption method. First an experiment was performed to see if water would completely fill closed voids in the resin and second a set of experiments was performed to determine if composites would behave as predicted in Figure 3.3.

First, to verify that voids will fill completely with water, a small sample of 5206 epoxy resin was carefully cast in such a way that one void approximately 0.08" in diameter was entrapped. A piece of the resin 0.15" x 0.20" x 0.40" was cut so that the void was located in the center of the specimen. The specimen was placed in boiling water for roughly 200 hours. After the water boil exposure it was weighed and its volume was determined; it was then ground down on a metallographic polishing wheel and reweighed. This cycle was continued several times until the specimen was nearly a spherical void within a small cube. The data obtained provided the density of water boiled resin (1.3 g/cc) and also the bulk density of the remaining portion of the specimen. The grinding procedure was continued until the void occupied 47% of the remaining cube. If no water filled the void bulk density would be 53% of 1.3 g/cc or .69 g/cc. The measured bulk density was 1.10 g/cc; theoretically if the void was completely filled the bulk density should be 1.16 g/cc and it is felt that if the water boil test would have been continued for a longer time that the entire void would have been filled. Nevertheless this was impressive evidence that the voids do fill with water.

Four additional experiments were performed on the remaining portions of the composite samples which were previously analyzed using metallography and conventional density techniques. Several specimens were water boiled for 140 hours, whereas the remaining specimens were oven dried at 212°F after only 70 hours in boiling water. The absorption curves are shown in Figure 3.4. The metallographic cross sections were shown in Figure 3.1. The water absorption and metallographic data are compared in Table 3.3, and as is evident an excellent correlation was obtained. This data implies several things. First that water fills only the resin and does not preferentially lie at the interface as found by Laird (Reference 13) in a glass epoxy composite; second that the voids are completely filled and the technique is accurate; and third that the water can be entirely removed from this composite.

As pointed out by Fried (Reference 12) glass reinforced plastics suffer a reduction in properties when exposed to moisture; however, some of these materials recover essentially all of their strength and stiffness when the water which was absorbed during immersion is removed.

It was natural to inquire whether or not the water absorption technique would affect the room temperature mechanical properties. Therefore, two 12 ply autoclaved panels (See Table 2.2, Group III) were used to evaluate the effects of a water boil/dry (WB/D) cycle on the mechanical properties of Modmor II/5206. Half of the specimens, the even numbered ones, were water boiled for 350 hours to determine porosity, then dried at 212°F for a similar length of time. The odd numbered specimens were stored at ambient conditions. Both groups were tested simultaneously. The results of the tests are presented in Appendix B and are summarized in Table 3.4. By performing a statistical analysis on the data it was possible to conclude with a 95% degree of confidence that the two groups, the WB/D and the virgin specimens, are from the same population. There was only one exception. This was the transverse flexure

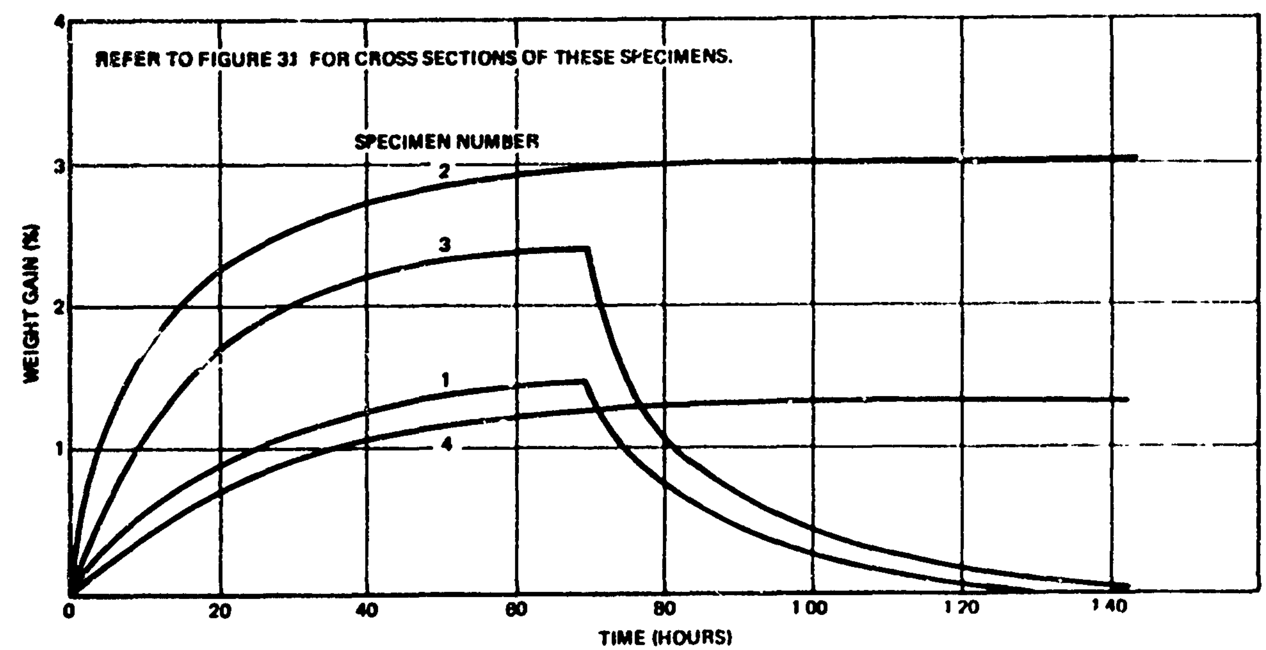


Figure 3.4 WATER ABSORPTION CHARACTERISTICS OF MODMOR II/5206 SPECIMENS

TABLE 3.3

POROSITY MEASUREMENT TECHNIQUES WATER ABSORPTION VERSUS METALLOGRAPHY

Specimen	Porosity	
	Metallography	Water Absorption
1	*	0.68
2	2.72	2.64%
3	1.75	1.74%
4	*	0

*Not Determined

Notes:

1. Cross section given in Figure 3.1.
2. Water absorption given in Figure 3.4.

specimens from panel 1109-59. The data from the WB/D group fell well below the data from virgin specimens. The WB/D specimens from this group had a small amount of residual moisture (.05%) which apparently had no effect on other properties but did significantly reduce the transverse flexural strength and modulus.

3.1.5 Discussion

The conventional methods for determining porosity which depend upon accurate density and weight fraction measurements of each component were briefly examined but, as found by others (Reference 1, 2, 3, and 14), were much too unreliable for use here where the porosity level was low and the specimen was relatively small.

Because of the shape and orientation of the voids within the laminate, cross sections taken perpendicular to the filament axis provide an accurate assessment of the volumetric porosity within the specimen. The development of automatic image analyzing equipment has reduced the time and effort required to analyze the data enormously. The metallographic point count technique still suffers from the fact that the specimen must be cut and hence cannot subsequently be mechanically tested; of if analyzed after testing, the microcracks (Reference 7) must be distinguished from voids.

The water absorption technique has been demonstrated to be an accurate method for determining porosity and if the specimens are subsequently dried, has been shown to have no effect on the mechanical properties.

3.2 Application of Porosity Techniques

3.2.1 Introduction

Two basic methods emerged from the investigation of void content techniques; water absorption which could be used prior to mechanical testing and metallography which was most effective when performed on specimens which were not mechanically tested. Hence, the 384 mechanical test specimens were subjected to a water boil/dry cycle prior to mechanical testing. The data on individual specimens will be presented along with the mechanical test data in a subsequent section. The porosity data will be summarized here in order to discuss the effects of the processing variables on porosity.

An additional 75 specimens referred to as void characterization specimens were cut from the same panels and were used to obtain further checks on the correlation between the water absorption and metallographic point count techniques.

3.2.2 Correlations Between Metallographic and Absorption Techniques

The 75 void characterization specimens were first oven dried for 70 hours at 212°F at which point the weight loss ceased. They were then placed into boiling distilled water. The specimens were periodically removed, their surfaces blotted dry and then air dried (70°F) for 10 minutes prior to weighing. The total immersion time in the boiling water was 300 hours. After this data was gathered the specimens were sectioned perpendicular to the filaments at their centerline, polished, and micrographs were taken which were analyzed by IMANCO. The complete data package is presented in Appendix C.

TABLE 3.4

SUMMARY OF WATER BOIL/DRY DATA

Type of Test	Panel	No. of Specimen	Treatment Prior to Test	Strength		Modulus		Residual Moisture (%)
				KSI	Cv	$\times 10^6$ psi	Cv	
Compression	1109-59	15	--	141	6			NA
Compression	1109-59	15	WB/D	137	10			0.05
Compression	1109-62	15	--	133	10			NA
Compression	1109-62	15	WB/D	133	8			0.00
Longitudinal	1109-59	8	--	242	5	21.0	2.8	NA
Flexure	1109-59	7	WB/D	254	4	20.9	0.7	0.07
Longitudinal	1109-59	8	--	247	6	21.7	6.2	NA
Flexure	1109-59	7	WB/D	245	4	21.0	1.2	0.00
Transverse	1109-59	8	--	13.5	7	1.45	2.8	NA
Flexure	1109-59	7	WB/D	10.8	7	1.36	5.5	0.05
Transverse	1109-62	8	--	12.7	12	1.43	3.7	NA
Flexure	1109-62	8	WB/D	12.1	6	1.43	2.3	0.00
Horizontal Shear	1109-59	15	--	16.3	3			NA
	1109-59	15	WB/D	16.2	3			0.06
Horizontal Shear	1109-62	15	--	16.4	2			NA
	1109-62	15	WB/D	16.2	3			0.00

WB/D = Water Boil/Dry
NA = Not Applicable

Cross sections from panels which were autoclave molded are similar to those shown in Figure 3.5. The water absorption curves indicate that the specimens have reached equilibrium and the resulting porosity data shows an excellent correlation with the point count data. In general the two techniques provide identical data. There were some specimens where the data conflicted which warrants additional discussion.

It must be recognized that a single cross section taken at the center of a specimen may not be truely representative of the average porosity which exists. An example of this is shown in Figure 3.6 where according to the micrographs the porosity in one specimen is 10%. Both the C-scan and the water absorption data imply that this specimen has the greatest porosity in that group but they imply that the porosity increases rather uniformly. The metallographic technique implies a very abrupt change which is felt to be due to a non-representative cross section.

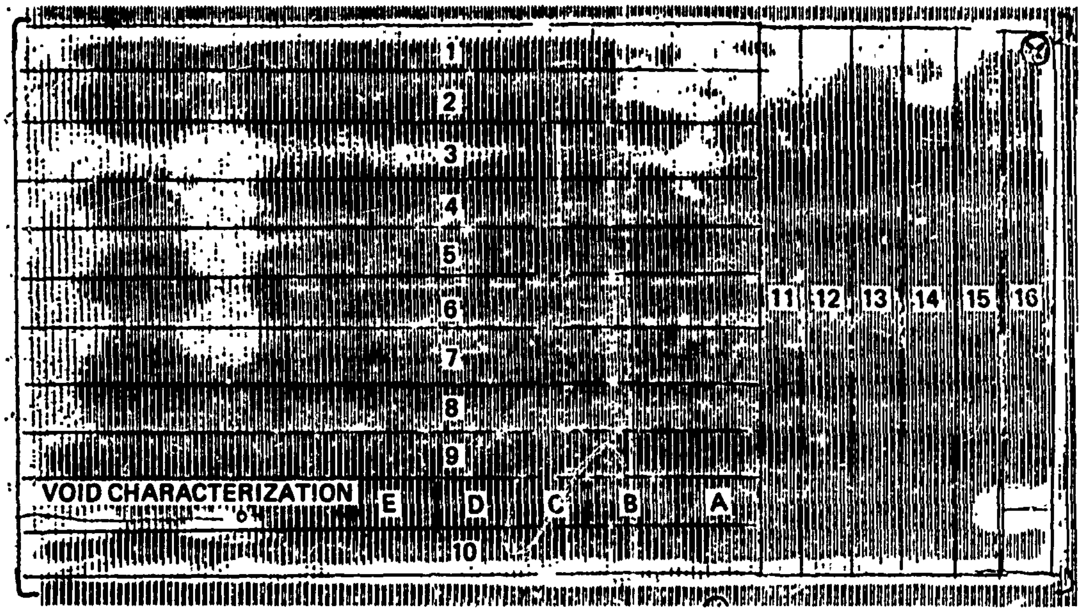
The conclusion is that the micrograph is not truely representative of the remainder of the specimen. By eliminating these data points an excellent correlation between the two techniques is again obtained. The same behavior was found in several specimens from two other panels and is attributed to the same phenomena.

It should not be thought that the use of automatic equipment is totally without bias. The contrast level (used to distinguish voids from other unwanted photographic information) must be preset by the operator. The method used by IMANCO is highly effective; however, when the lighting varies significantly over micrograph the data may be in error. For example a visual observation of the photographs in Figure 3.7 indicate a high degree of uniformity. This is substantiated by the water absorption curves and data. The point count data indicate no porosity in 6 of the 8 specimens. This is clearly contradictory to visual observations and is attributed to non-uniform lighting effects on the image analyzer.

A basic premise underlying the validity is that the voids become full of water. This implys that the water absorption curves have reached an equilibrium condition where no further absorption takes place. This condition was not achieved with specimens from the vacuum bag molded panels (high porosity panels). The voids therefore are only partially filled and hence the data will provide porosity levels lower than the true void content. For this reason the data was handled in the following way. The water absorption data at 300 hours was used to compute an apparent void content. This apparent void content was adjusted by using the point count data as a reference. The following relation was used:

$$(\text{True Porosity}) = K\ (\text{Apparent Porosity})$$

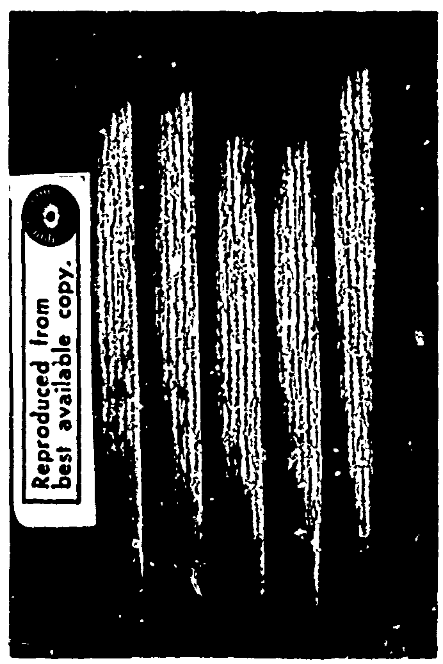
K is therefore a modification factor which permits the computation of porosity from non-equilibrium water absorption data. Panel 1109-37 (See Figure 3.8) was chosen for obtaining the modification factor for several reasons: (1) a large number of samples were analyzed from this panel, (2) water absorption data correlates well with C-scan, and (3) the micorgraphs are reasonably uniform in appearance. Assuming the metallographic data to be representative, the modification factor is $\frac{7.50}{5.42} = 1.38$. Checking with data from other vacuum bag molded panels shows this factor to be reasonable and hence, for lack of a more sophisticated technique to adjust for non-equilibrium data, was used.



C-SCAN OF PANEL 1109-53

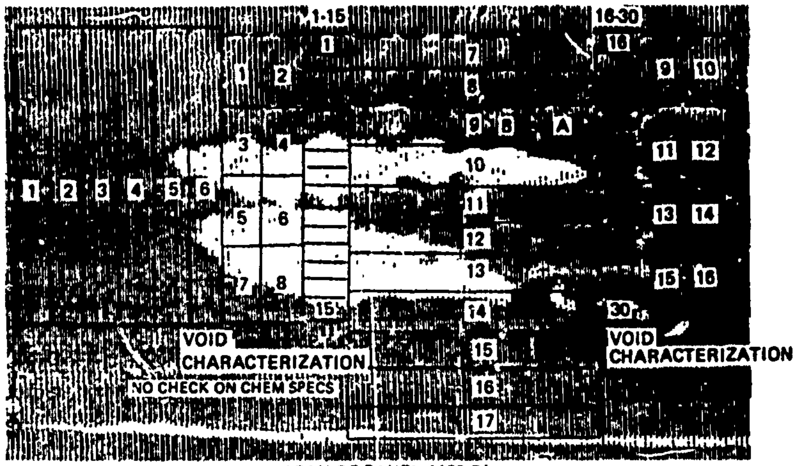
SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-53 AC/ES, 0° 6 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
A	.35	.52	.07
B	.4	.60	.16
C	.2	.30	.33
D	.1	.15	.28
E	.1	.15	.38
		$\overline{X}$.34	$\overline{X}$.24

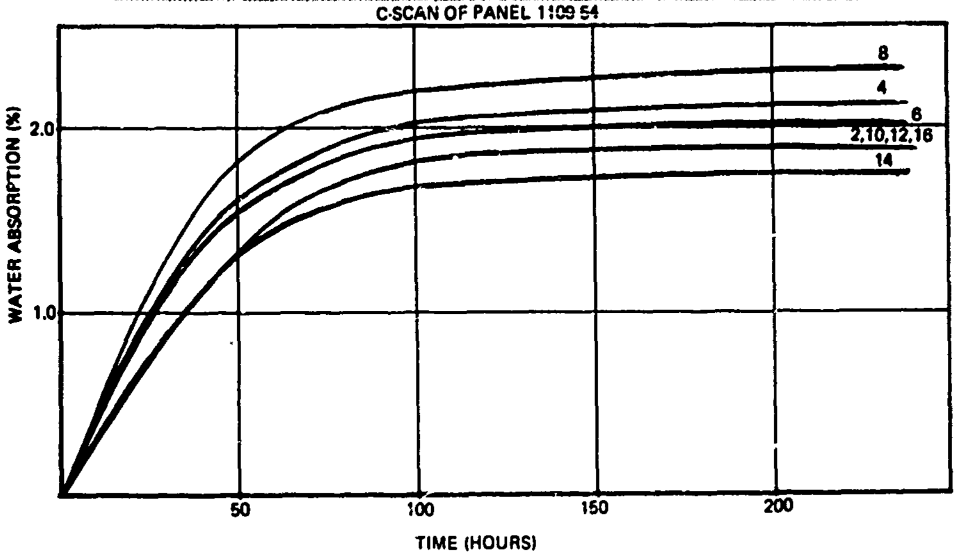


A B C D E
PHOTOMICROGRAPHS

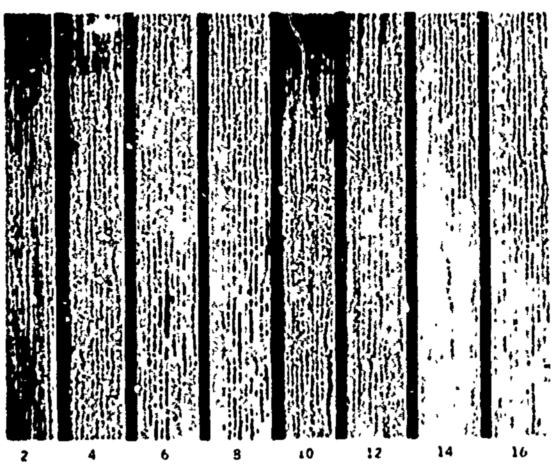
Figure 3.5 POROSITY DATA FROM PANEL 1109-53



C-SCAN OF PANEL 1109 54



WATER ABSORPTION CURVES FOR VOID CHARACTERIZATION SPECIMENS

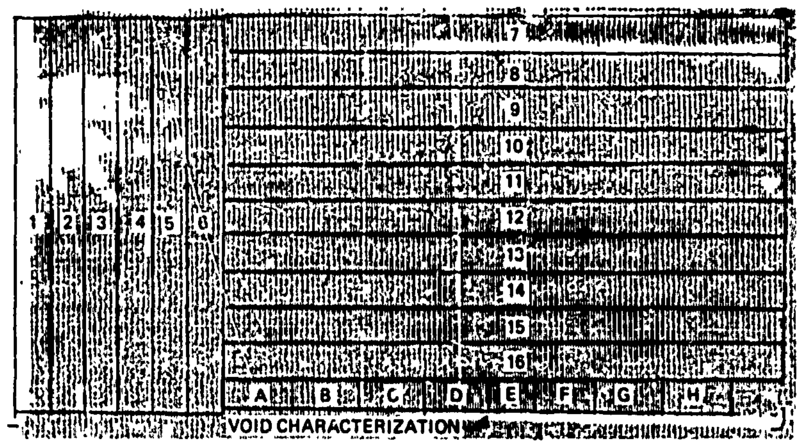


SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-54 AC/ES, 0° 12 PLY

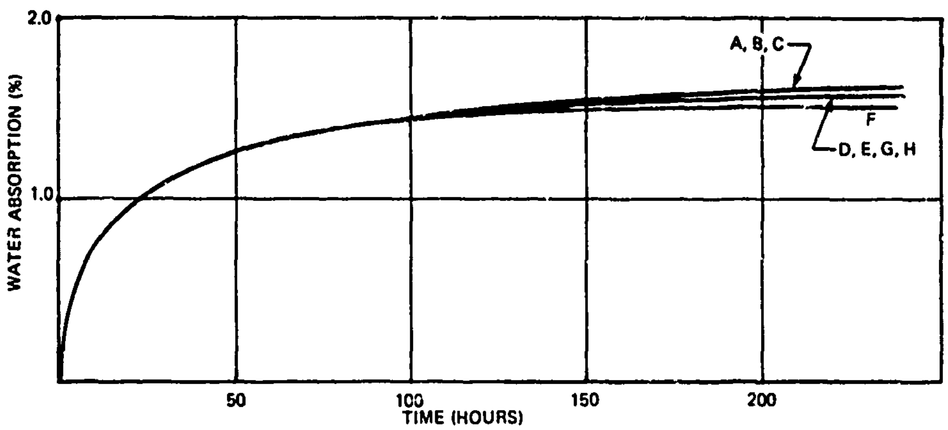
	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
2	.6	.9	3.3
4	.85	1.27	2.4
6	.8	1.2	4.8*
8	1.8	2.7	10.4*
10	.6	.9	1.4
12	.6	.9	.37
14	.45	.67	.21
16	.6	.9	1.19
		$\bar{X}$1.18	$\bar{X}$3.00

*Not a truely representative cross section of the specimen.

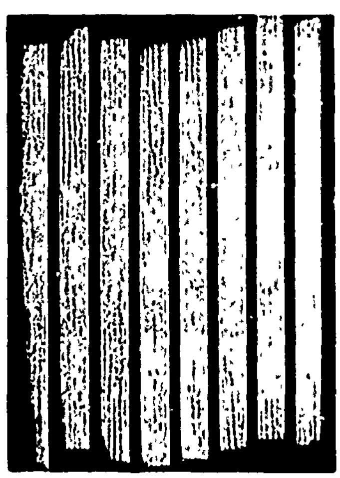
Figure 3.6 POROSITY DATA FROM PANEL 1109-54



C-SCAN OF PANEL 1109-40



WATER ABSORPTION CURVES

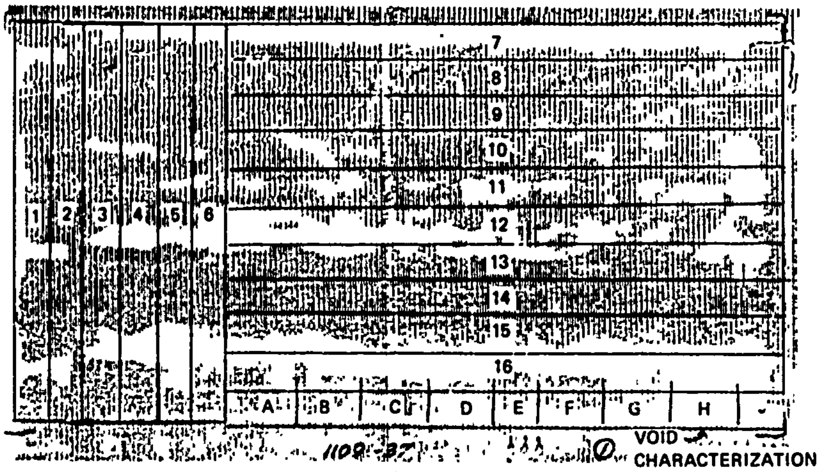


PHOTOMICROGRAPHS

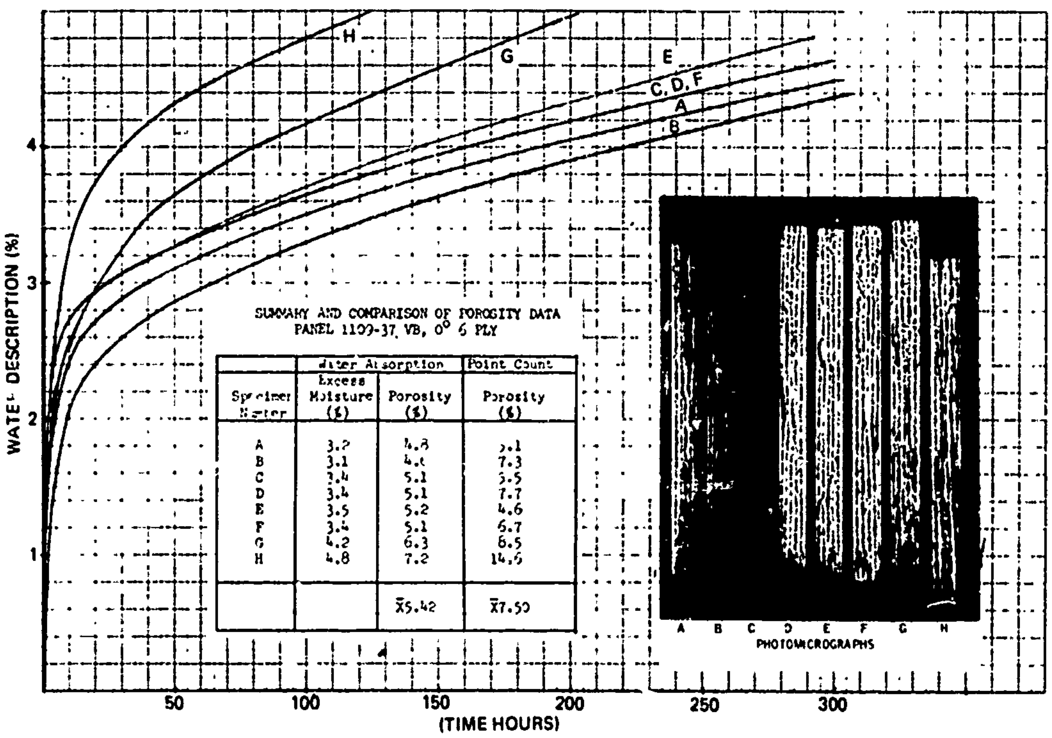
SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-40 AC, 0° 6 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
A	.36	.54	0
B	.36	.54	0
C	.36	.54	0
D	.34	.51	.4
E	.34	.51	.4
F	.24	.36	0
G	.34	.51	0
H	.34	.51	0
		$\bar{X}$ .50	$\bar{X}$ .1

Figure 3.7 POROSITY DATA FROM PANEL 1109-40



C-SCAN OF PANEL 1109-37



SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-37, VB, 0° 6 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
A	3.2	4.8	5.1
B	3.1	4.6	7.3
C	3.4	5.1	5.5
D	3.4	5.1	7.7
E	3.5	5.2	4.6
F	3.4	5.1	6.7
G	4.2	6.3	6.5
H	4.8	7.2	14.5
		$\bar{X}$5.42	$\bar{X}$7.50

WATER ABSORPTION CURVES

Figure 3.8 POROSITY DATA FROM PANEL 1109-37

As a result of the overall findings the water absorption technique is felt to be extremely useful and eliminates the need for taking multiple cross sectional micrographs of each specimen. A discrepancy exists between the water boil and metallographic data when non-equilibrium absorption curves were used. This is of course expected and involves only the data on the vacuum bag panels. Had more time been available, the water absorption tests would have been conducted for a longer period. Nevertheless, by using the metallographic data to obtain an adjustment factor, the non-equilibrium water absorption data could be suitably corrected.

3.2.3 Porosity Variations in the Laminates

By means of the water absorption technique the porosity for each specimen cut from the panel was determined and is presented in Appendix D. The data is superimposed on the C-scan and show this technique to be sufficiently sensitive to detect small variations in porosity. For example refer to the void characterization specimens from panel 1109-37. The attenuation and porosity data increase in a uniform fashion as was also found by Hand (Reference 15). In panels 1109-39 and 1109-54 half of the short beam shear specimens were cut from a high attenuation area and were found to have an abnormally high porosity which, incidentally, was reflected in shear strength. As for the cross ply laminates a good example is 1109-55 where the 0^{o} specimens were cut from the portion of the panel having the highest attenuation, and as the data indicates, there specimens had a porosity of approximately 1.3% whereas the remainder of the panel had an average porosity of 0.7%. These are just a general sample of the correlation found between the water absorption which indicates porosity and the ultrasonic C-scan evaluation and indicates the usefulness of this standard nondestructive test technique in determining panel quantity.

Some further and more condensed information regarding the porosity variations which arise from the processing techniques used is presented in Table 3.5. The average porosity and their extremes are given for data gathered on the mechanical test specimens. The following conclusions can be drawn: Vacuum bag molding results in an average porosity of approximately 5%. Autoclave molding reduces the porosity to approximately the .6% level. The exact values are dependent upon the amount of solvent in the prepreg. The advanced prepreg which had additional solvent added had a substantially higher void content and the standard prepreg was found in between these levels.

The variations seen within a panel are shown in the next section to influence the mechanical properties.

TABLE 3.5

LAMINATE POROSITY (AVERAGES)

Panel	Molding	Layup	Average Porosity	High	Low
1109-37	VB	12 Ply UD	4.45	5.83	3.31
1109-40	AC	12 Ply UD	.37	.65	0
1109-53	AC/ES	12 Ply UD	.92	1.55	.71
1109-56	AC/AP	12 Ply UD	.36	.52	.24
1109-36	VB	6 Ply UD	5.72	8.70*	4.35
1109-39	AC	6 Ply UD	.27	1.31	0
1109-54	AC/ES	6 Ply UD	1.38	2.95	.71
1109-57	AC/AP	6 Ply UD	.14	.30	0
1109-38	VB	7 Ply 0/90°	4.61	5.46	3.32
1109-41	AC	7 Ply 0/90°	.38	1.41*	.19
1109-55	AC/ES	7 Ply 0/90°	1.00	1.90*	.68
1109-58	AC/AP	7 Ply 0/90°	.28	.65*	.19

*Near the edge of a panel.

VB = Vacuum Bag

AC = Autoclave

ES = Excess Solvent (1% MEK)

AP = Advanced Prepreg (72 Hour Air Dry)

UD = Unidirectional Reinforcement

4.0 THE EFFECT OF VOIDS ON MECHANICAL PROPERTIES OF MODMOR II/5206

4.1 Introduction

The mechanical test program was designed to meet three objectives (1) that preliminary design information be evaluated, this implys tensile and compressive strengths, moduli, and strain to failure, (2) that quality control information such as short beam shear and flexural properties be evaluated and, (3) that cross ply laminates be studied in order to determine the correlation as a function of void content between unidirectional and bi-directional composites. Thus the program not only evaluates the more fundamental effects on unidirectional composites but also considers the more structurally useful cross ply laminates.

The cross ply that was chosen was intended for a specific purpose. The laminate had a 0/90/0/90/0/90/0° layup. In the primary directions full laminate efficiency can be achieved only if the load is transferred by shear from the outer layers, to which the tabs are bonded, to the inner ones. Lenoe's work showed that porosity greatly decreased the shear strength and hence may affect the tensile strength of this particular type of laminate.

4.2 Materials

Twelve panels were fabricated for this portion of the study; three using four different molding techniques (Refer to Table 2.2). Based upon the void characterization studies (Section 3.0) the processing techniques resulted in the average porosities given in Table 4.1.

4.3 Specimen Geometry and Test Procedure

4.3.1 Tension

Tension tests were performed in the 0° (longitudinal) and 90° (transverse) direction on unidirectional, 6 ply laminates and in the 0°, 45°, and 90° direction on the bi-directional, 7 ply laminates. All specimens were straight sided and ½" wide. The transverse tests on the unidirectional material were performed on 6" long specimens; all other specimens were 9" long. Strain measurements on tensile specimens were made using a 1" gage length extensometer.

Prior to mechanical testing 1/8" thick and 2" long fiberglass tabs were bonded to each specimen. A 45° chamfer was used to feather the tab into the gage section. A total of 136 tensile tests were performed, a specific breakdown of each type is given in Table 2.2.

4.3.2 Flexure

Longitudinal and transverse flexure tests were performed on 12 ply unidirectional composites. The specimens were 4" long and ½" wide. The longitudinal tests were performed using 3 point bending over a 2½" span. The transverse flexure tests were constructed using 4 point bending over a 2" span; the two central load points were 1" apart. Sixty-four flexure tests in all were performed; Table 2.2 defines the number of tests performed on each panel.

TABLE 4.1

POROSITY IN MODMOR II/5206

Specimen	Layup	Molding	Average Porosity
1109-37	12 Ply UD	VB	4.45
1109-40		AC	0.37
1109-53		AC/ES	0.92
1109-56		AC/AP	0.36
1109-36	6 Ply UD	VB	5.72
1109-39		AC	0.27
1109-54		AC/ES	1.38
1109-57		AC/AP	0.14
1109-38	7 Ply 0/90	VB	4.61
1109-41		AC	0.38
1109-55		AC/ES	1.00
1109-58		AC/AP	0.28

VB = Vacuum Bag

AC = Autoclave

ES = Excess Solvent (1% MEK)

AP = Advanced Prepreg (Air Dry)

4.3.3 Horizontal Shear

Short beam shear tests were performed on specimens cut from 12 ply unidirectional panels. These specimens were $\frac{1}{2}$" wide and 0.6" long. They were tested in 3 point bending using a 0.4" span. The resulting span to depth ratio was 4.7. Thirty specimens from each of the 4 panels were tested (See Table 2.2).

4.3.4 Compression

The compression strength was determined in the fiber direction using the 12 ply unidirectionally reinforced laminates. The specimens were $\frac{1}{2}$" wide and 1" long but were constrained by clamps at each end so that only a $\frac{1}{2}$" length was unsupported. As shown in Table 2.2, 16 specimens from each of the 4 panels were tested.

4.4 Nondestructive Tests

4.4.1 C-scan

Prior to machining a C-scan record was taken of all the panels. The techniques and general results were described in (Section 3.0) and will not be reiterated here. Specific data will be referred to as needed.

4.4.2 Ultrasonic Velocities

Other researchers have noted a decrease in ultrasonic velocity with increases in porosity (Reference 1, 2, and 3) had hence the technique was employed here. Data was obtained on specimens from the autoclave and vacuum bag molded laminates and is presented in its entirety in Appendix E. A summary is given in Table 4.2. Since the velocity is somewhat dependent upon specimen geometry, comparisons can be made only between identical types of specimens. As can be seen, in general the porosity results in a decrease in ultrasonic velocity. The data on the short beam shear specimens was broken up into two groups. Each group was taken from a different portion of the panel and as was shown from the C-scans in Section 3.0 the porosity level for specimens numbered 1 through 15 differed from the group containing specimens 16 through 30. This is most apparent in specimens from panel 1109-39. The difference in the mean velocities is significant at the 95% confidence level and as will be shown the mechanical properties differ significantly also. The C-scan data on the vacuum bag panel (1109-36) indicated a more even distribution of porosity in both groups of short beam shear specimens; the mean velocity of each group here differs but only at the 90% confidence level.

The variations seen in the data from all other groups of unidirectional specimens differ at the 95% confidence level. However, the cross ply data is not sensitive to porosity. This is attributed to the wave distortions which result in difficulties in accurately measuring the transit time.

TABLE 4.2

SUMMARY OF ULTRASONIC VELOCITY DATA

Specimen Type (1)	Velocity Measurement (orientation)	Panel	Specimens	Molding Technique (2)	Velocity Average (fps)	Velocity Coef. of Var. (%)	Average Porosity	C-Scan Attenuation
SBS	Parallel to Fibers	1109-36	(1-15)	VB	44675	3.7	5.7	About equal - both high
SBS	Parallel to Fibers	1109-36	(16-30)	VB	44002	2.3	6.0	About equal - both high
SBS	Parallel to Fibers	1109-39	(1-15)	AC	46410	2.2	0.0	Low - but (16-30) group
SBS	Parallel to Fibers	1109-39	(16-30)	AC	45759	2.5	0.7	is higher
LF	Parallel to Fibers	1109-36	all	VB	32021	0.7	5.8	High
LF	Parallel to Fibers	1109-39	all	AC	32800	0.9	0.1	Low
LT	Parallel to Fibers	1109-37	all	VB	32173	1.5	4.49	High
LT	Parallel to Fibers	1109-40	all	AC	32658	1.4	0.28	Low
TF	Perpendicular to Fibers	1109-36	all	VB	8043	0.6	5.8	High
TF	Perpendicular to Fibers	1109-39	all	AC	8145	0.2	0.0	Low
TT	Perpendicular to Fibers	1109-37	all	VB	8017	0.4	4.54	High
TT	Perpendicular to Fibers	1109-40	all	AC	8284	0.3	0.51	Low
Cross Ply	Parallel to 0° Fibers	1109-38	all	VB	20162	6.9	4.5	High
Cross Ply	Parallel to 0° Fibers	1109-41	all	AC	20129	3.5	.3	Low
Cross Ply	Parallel to 90° Fibers	1109-38	all	VB	22308	2.3	4.5	High
Cross Ply	Parallel to 90° Fibers	1109-41	all	AC	22736	2.4	.6	Low

1) SBS - Short Beam Shear, LF - Longitudinal Flexure, LT - Longitudinal Tension, TF - Transverse Flexure
TT - Transverse Tension

Cross Ply - 0/90° Tension Specimens

2) VB - Vacuum Bag, AC - Autoclave

TABLE 4.3

SUMMARY OF THE EFFECT OF POROSITY ON TENSILE PROPERTIES OF UNIDIRECTIONAL LAMINATES

Type of Test	Material	Panel	Fabrication Technique	Property							
				Strength		Modulus		Strain		Porosity	
				$\bar{X}$	Cv	$\bar{X}$	Cv	$\bar{X}$	Cv	$\bar{X}$	Cv
				(psi)	(%)	$x10^6$ psi	(%)	(%)	(%)	(%)	(%)
LT	6 Ply UD	1109-37	VB	155,000	15.3	18.3	5.2	.80	9.9	4.4	12.0
		1109-40	AC	157,000	10.0	21.4	7.2	.73	6.1	.3	- -
		1109-53	AC/ES	153,000	13.3	20.1	4.2	.77	12.1	1.0	- -
		1109-56	AC/AP	177,000	9.9	20.1	4.7	.87	12.8	.4	- -
TT	6 Ply UD	1109-37	VB	4,320	11.0	1.06	5.4	.41	8.6	4.5	15.0
		1109-40	AC	4,450	6.7	1.18	4.1	.39	8.2	.5	- -
		1109-53	AC/ES	6,140	7.9	1.25	4.0	.51	8.9	.8	- -
		1109-56	AC/AP	4,290	8.9	1.24	4.2	.34	11.1	.3	- -

LT = Longitudinal Tension

TT = Transverse Tension

UD = Unidirectional Reinforcement

VB = Vacuum Bag

AC = Autoclave

ES = Excess Solvent (1% MEK)

AP = Advanced Prepreg (Air Dry)

The relation between porosity and C-scan attenuation has been previously discussed and the results indicated that attenuation of acoustic energy is highly sensitive to porosity. On the other hand ultrasonic measurements are only slightly sensitive to porosity. For example the greatest variation seen occurred in the short beam shear specimens. Here a 6% porosity level resulted in a 5% velocity decrease as compared to void free specimens. Other types of specimens, flexure and tensile, show approximately a 2% decrease in velocity for a 5% void content. As will be shown subsequently the mechanical properties are more sensitive on a percentage decrease basis than a . hese velocity measurements. Further, the velocity data was inconclusive on the cross ply laminates and these are the types which are of primary interest in aircraft structures.

4.5 Mechanical Properties - The Effect of Porosity

A total of 384 specimens were tested in this phase of the program. All except 32 of the compression specimens were subject to a water boil/dry cycle prior to testing. The porosity and ultrasonic velocity data are included in the tables along with the mechanical properties, thereby making the correlations between each readily available. Since the complete data is voluminuous it is presented in Appendix F; only a summary is given in the text.

4.5.1 Effect of Porosity on Unidirectional Tension Properties

The longitudinal and transverse tensile properties are summarized in Table 4.3 and for ease of comparison the data was plotted on graphs having porosity as the abscissa. As can be seen in Figure 4.1 and 4.2, the strength and modulus decrease by roughly 10% as the porosity increases to a level of 5%. Most of the data was obtained for porosities of less than 1% and the data suggests that only at levels of porosity greater than 1% is the degradation significant.

Several items are noteworthy. First the strain to failure which is summarized in Table 4.3 is highly insensitive to porosity. It is about 0.80% in the longitudinal direction and 0.45% in the transverse direction. Second, the longitudinal strength and modulus are greater and the transverse strength lower than previous data obtained on virgin material (Section 2.0, Table 2.4). This is possibly due to the small amount of residual moisture but may reflect panel to panel variations inherent in these materials.

The velocity data was found to vary by a statistically significant amount and therefore a plot of velocity versus porosity as shown in Figure 4.3 is valid. However, it must be pointed out that the coordinate system chosen visually exaggerates the sensitivity of the velocity data. A simple comparison of actual data points show that the velocity varies by more than 3% whereas the mechanical modulus varies by at least 13%.

4.5.2 Effect of Poros' on Shear Strength

The shear strength is highly sensitive to porosity and this is perhaps due to the fact that in these composites the voids tend to lie in between plys. The data is summarized in Table 4.4. Often the shear strength from specimens 1-15 differs significantly from data obtained from specimens 16-30. A look at the C-scan data for these panels is enlightening. In all cases where there was variation in strength it was picked up by the C-scan. The most noticeable variation occurs in panel 1109-39. Specimens 1-15 have a high shear strength

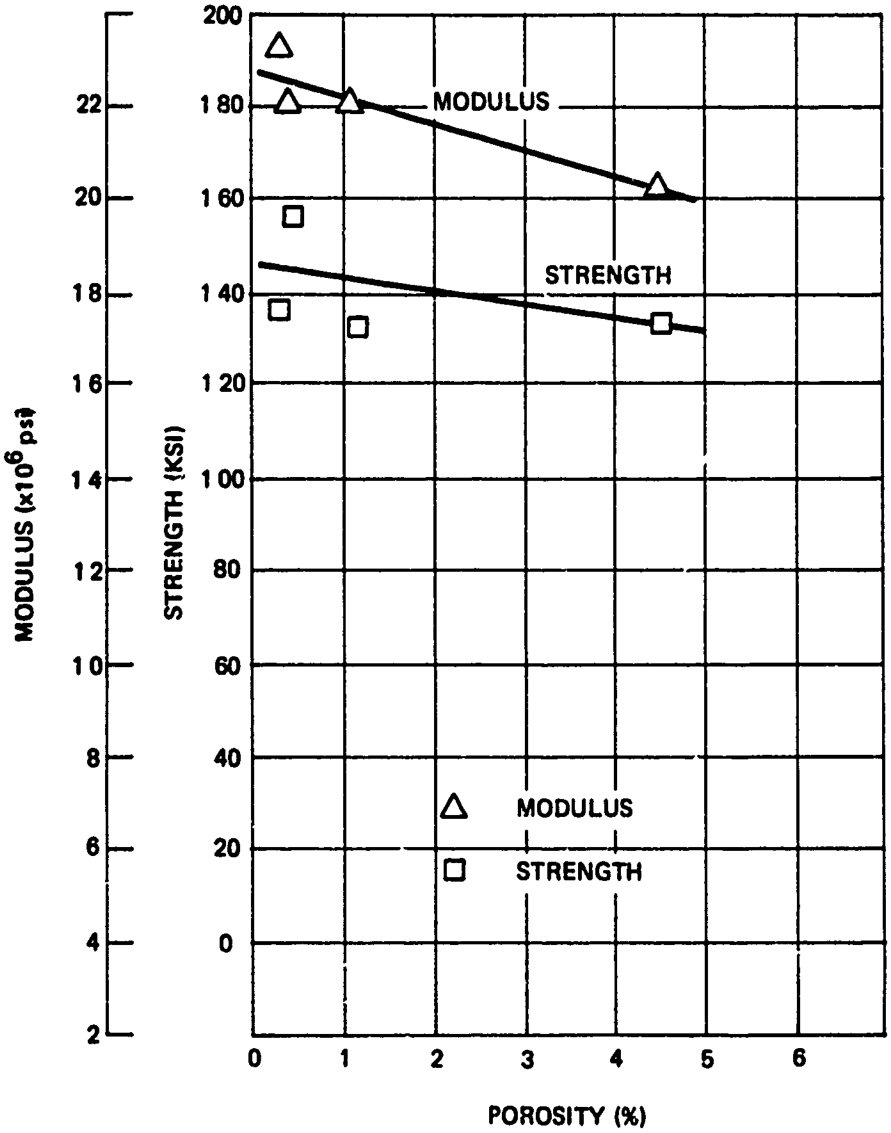


Figure 4.1 LONGITUDINAL TENSILE PROPERTIES

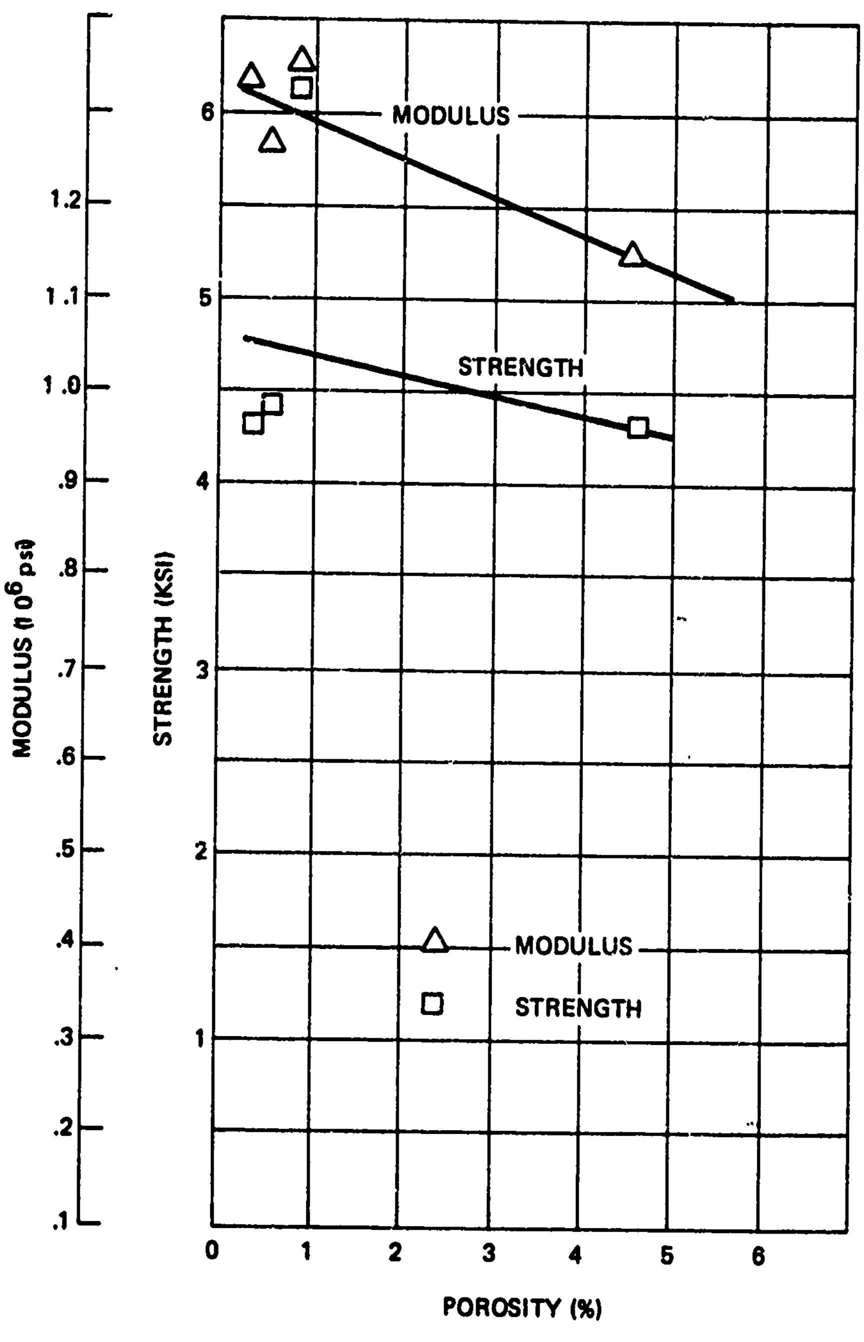


Figure 4.2 TRANSVERSE TENSILE PROPERTIES

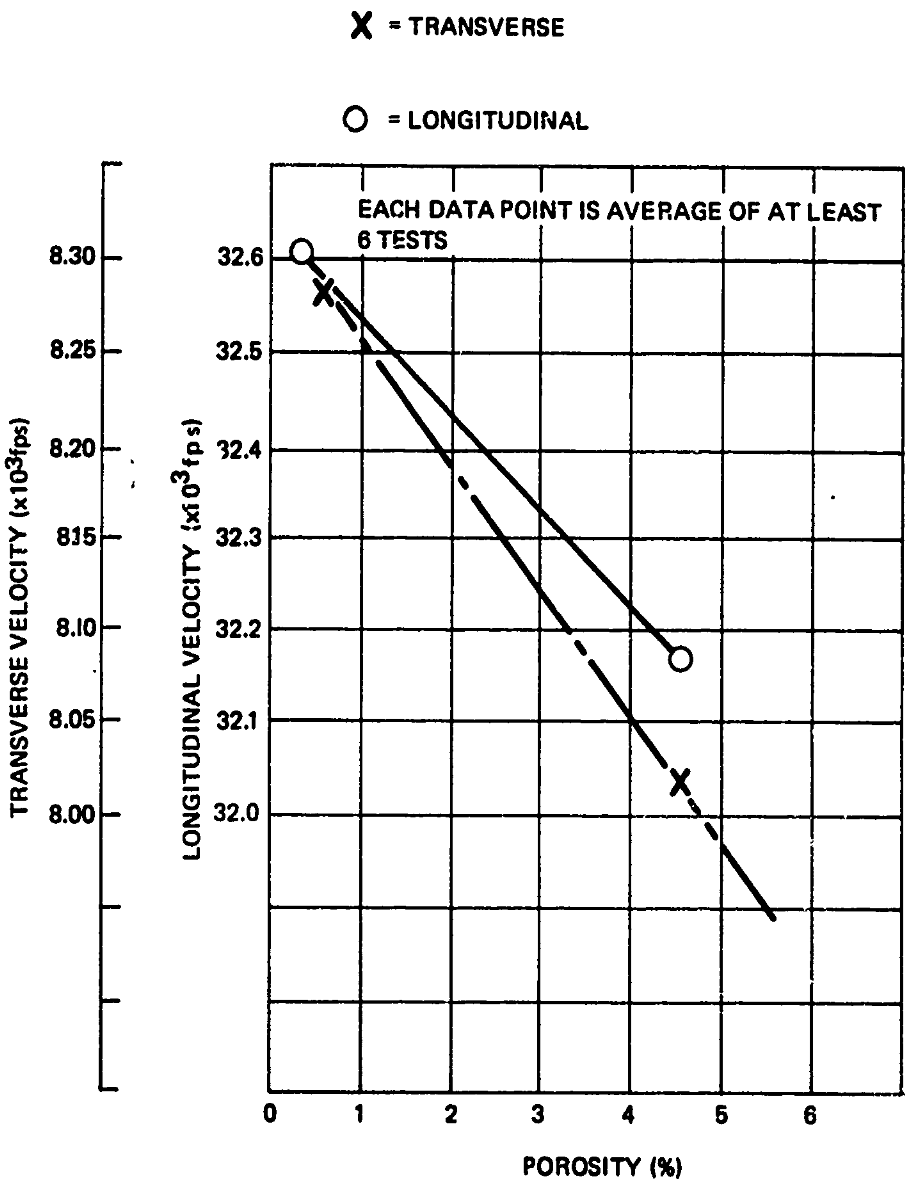


Figure 4.3 VELOCITY IN TENSION SPECIMENS AS A FUNCTION OF POROSITY

(16,200 psi), a high sonic velocity, a low porosity (as determined by the water absorption curves), and a low acoustic attenuation as indicated on the C-scan. The opposite is true for specimens 16-30 which were machined from a different portion of the same panel. As shown graphically in Figure 4.4 the horizontal shear strength is a sensitive indicator of porosity. Over the porosity range from 0 to 6% the shear strength varies in a relatively uniform manner by a factor of 50%.

The ultrasonic velocity as shown in Figure 4.5 by plotting also varies strongly enough to give some indication of porosity.

In summary the correlation between porosity, strength, and acoustic attenuation (C-scan) is excellent. The ultrasonic velocity is a low sensitivity measure of porosity and varies by only 5% whereas the shear strength varies by 50%.

4.5.3 Effect of Porosity on Compressive Strength

Porosity was determined in only 32 specimens (half of the total population). The groups studied however cover the primary range of porosities. The vacuum bag molded specimens had an average porosity of 5.6% and the resultant strength was 111 KSI. The autoclave molded specimens had a negligible porosity (.3%) and had a compressive strength of 157 KSI. The data is plotted in Figure 4.6.

Specimens from panels 1109-54 and 1109-57 were not water boiled and hence represent virgin material. Comparing the data which is given in Table 4.5 it can be seen that these two virgin panels have strengths significantly (based upon statistical techniques) lower than panel 1109-39 and autoclaved panel which has comparable porosity but which was subjected to the water boil dry cycle. The strengths of these panels (1109-57 and 1109-54) are comparable to data obtained earlier (Section 3.0) from other virgin material (panels 1109-59 and 1109-62). Hence we must conclude either that the water/boil dry cycle enhanced the strength in panel 1109-39 or that this material of exceptionally high quality.

4.5.4 Effect of Porosity on Flexural Properties

The flexural data is summarized in Table 4.6. Graphically in Figures 4.7 and 4.8 it can be seen that the properties diminish as the porosity increases. The modulus decreases roughly 18% and the strength 27% regardless of orientation. The longitudinal properties on void free material are slightly lower than those obtained earlier on virgin material which was also autoclave molded (See Section 3.0 panels 1109-59 and 1109-62). The transverse modulus is identical to the value obtained previously; the average strength however is significantly reduced. Again this may be due to a slight amount of retained moisture as was discussed in Section 3.0 or possibly just reflects material variability.

It is interesting to note that the highest transverse properties are obtained on the material which was made by autoclave molding prepreg containing excess solvent which resulted in a porosity of 0.9% in these specimens. The significance of this is not known but the same result was found for transverse tensile properties.

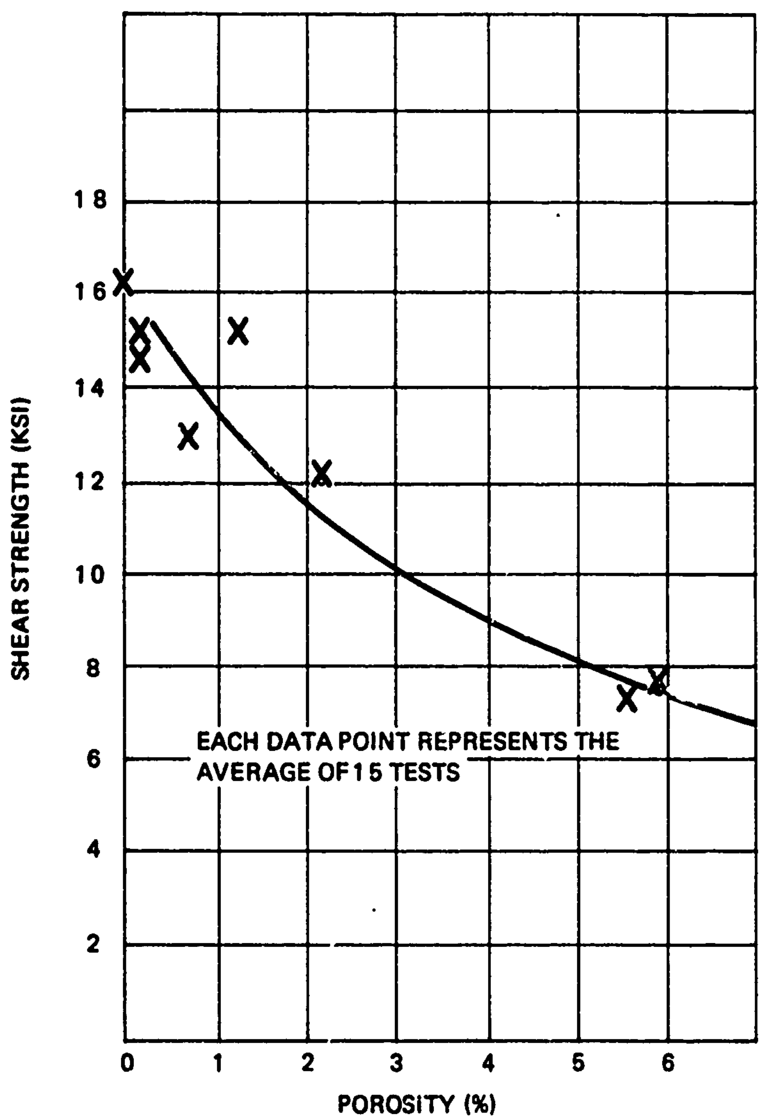


Figure 4.4 HORIZONTAL SHEAR STRENGTH

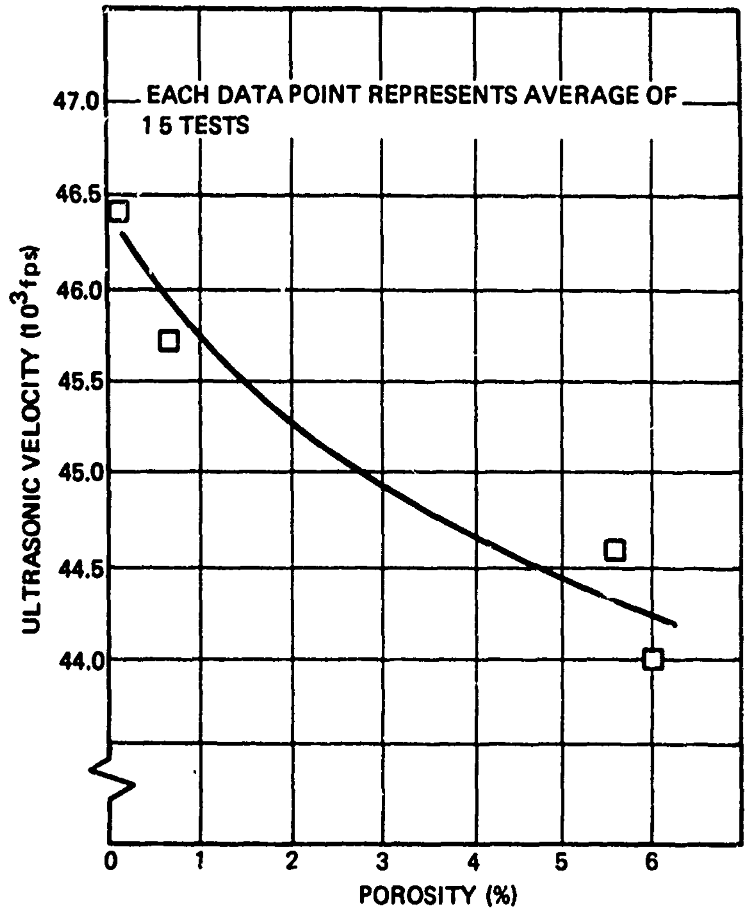


Figure 4.5 ULTRASONIC VELOCITY IN THE SHEAR SPECIMENS AS FUNCTION OF POROSITY

TABLE 4.4

SUMMARY OF THE EFFECT OF POROSITY ON THE SHEAR STRENGTH OF UNIDIRECTIONAL LAMINATES

Type of Test	Material	Panel	Specimen	Property: Strength Average PSI	Property: Strength Cv (%)	Property: Porosity Average (%)
SBS	12 Ply UD - VB	1109-36	1-15	7,140	13.0	[illegible].71
SBS	12 Ply UD - VB	1109-36	16-30	7,770	8.0	[illegible].00
	Data For Entire Group			7,450	1[illegible]	5.85
SBS	12 Ply UD - AC	1109-39	1-15	16,200	4.0	0.04
SBS	12 Ply UD - AC	1109-39	16-30	12,900	11.0	0.67
	Data For Entire Group			14,600	13.0	0.36
SBS	12 Ply UD AC/ES	1109-54	1-15	12,200	13.0	2.11
SBS	12 Ply UD AC/ES	1109-54	16-30	15,100	6.0	1.12
	Data For Entire Group			13,600	14.0	1.66
SBS	12 Ply UD AC/AP	1109-57	1-15	14,700	6.0	0.12
SBS	12 Ply UD AC/AP	1109-57	16-30	15,300	2.0	0.17
	Data For Entire Group			15,046	5.0	0.14

SBS - Short Beam Shear

VB - Vacuum Bag

AC - Autoclave

ES - Excess Solvent

AP - Advanced Prepreg

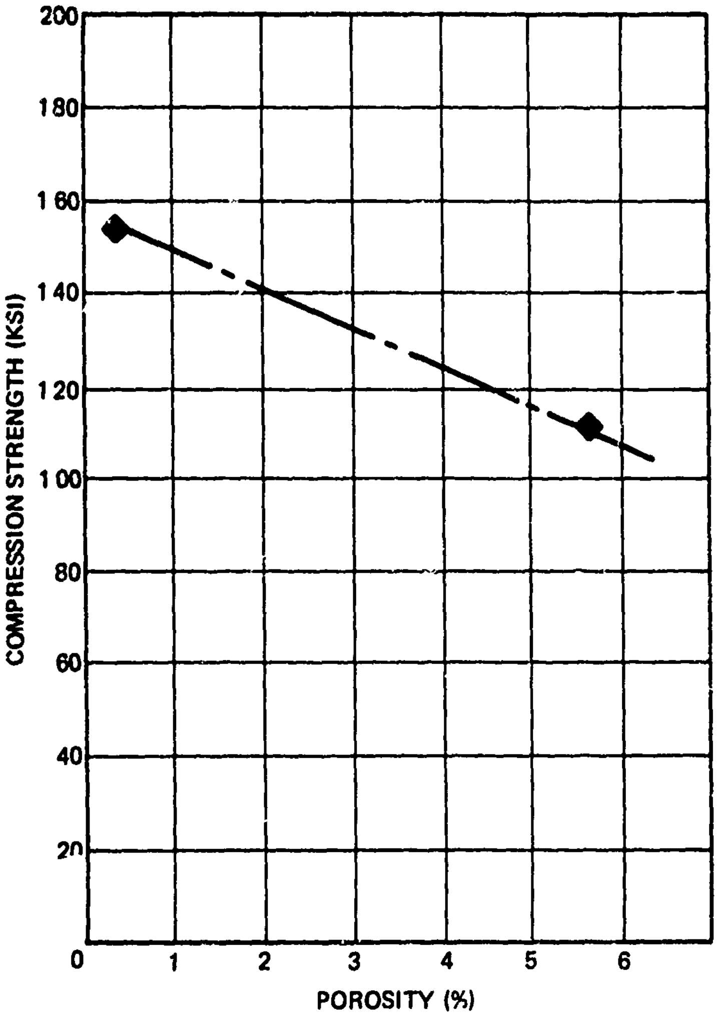


Figure 4.6 COMPRESSION STRENGTH

TABLE 4.5

SUMMARY OF THE EFFECT OF POROSITY ON THE COMPRESSION STRENGTH OF UNIDIRECTIONAL LAMINATES

Type of Test	Material	Panel	Fabrication Technique	Property: Strength $\bar{X}$ (KSI)	Strength Cv (%)	Porosity $\bar{X}$ (%)	Porosity Cv (%)	Notes
Compression	12 Ply UD	1109-36	VB	111	22	5.6	14	WB/D
Compression	12 Ply UD	1109-39	AC	157	9	.3	--	WB/D
Compression	12 Ply UD	1109-54	AC/ES	133	15	ND		Virgin
Compression	12 Ply UD	1109-57	AC/AP	126	15	ND		Virgin

ND - Not determined on these particular specimens however the porosity should be approximately the same as the averages given in Table 4.1.

VB - Vacuum Bag

AC - Autoclave

ES - Excess Solvent (1% MEK)

AP - Advanced Prepreg (Air Dry)

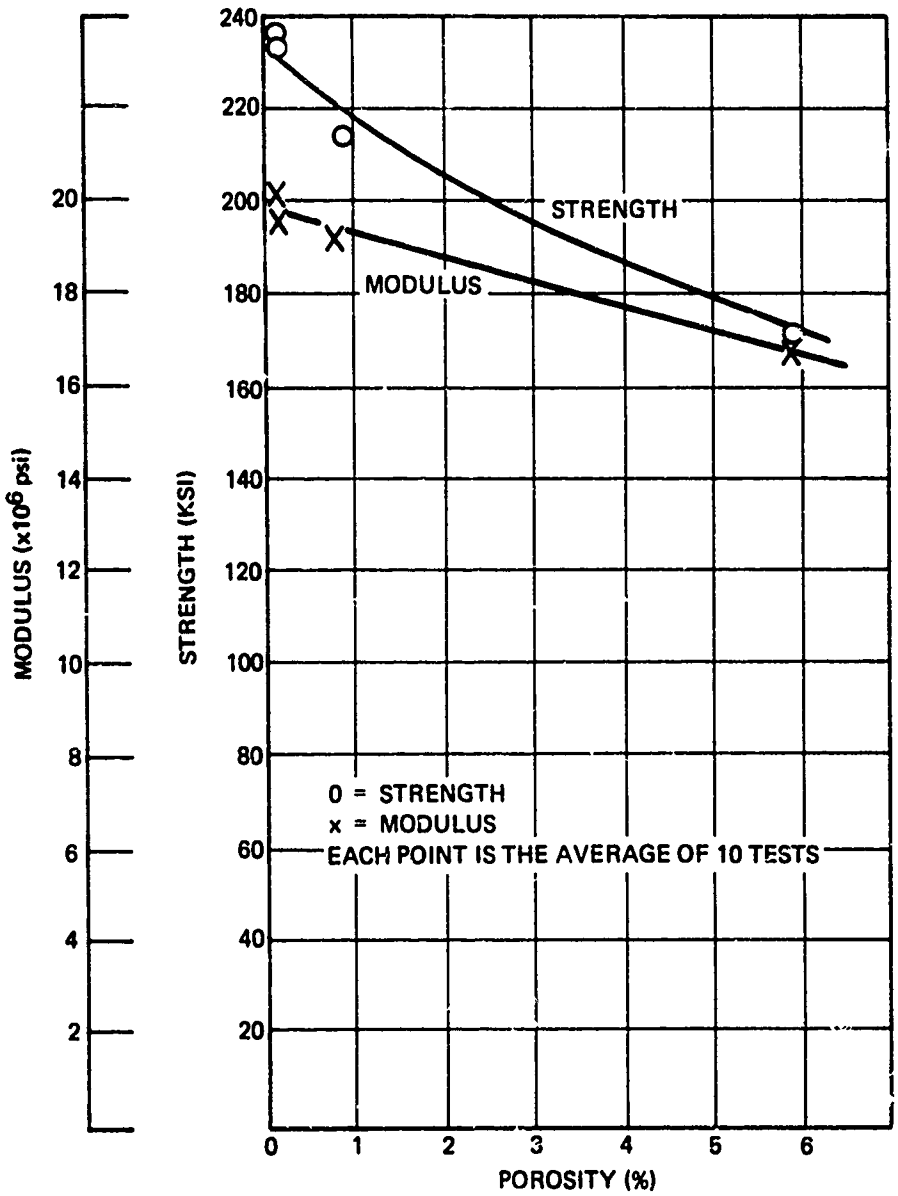


Figure 4.7 LONGITUDINAL FLEXURAL PROPERTIES

TABLE 4.6

EFFECT OF POROSITY ON THE FLEXURE PROPERTIES
OF UNIDIRECTIONAL LAMINATES

Type of Test	Material	Panel	Fabrication Technique	Property					
				Strength		Modulus		Porosity	
				X	Cv	X	Cv	X	Cv
				psi	%	x10⁶psi	%	%	%
LF	12 Ply UD	1109-36	VB	171,000	3.9	17.0	5.8	5.81	9.0
		1109-39	AC	236,000	8.0	20.2	2.2	0.14	- -
		1109-54	AC/ES	212,000	4.9	19.0	5.5	0.86	- -
		1109-57	AC/AP	237,000	4.8	19.4	7.8	0.03	- -
TF	12 Ply UD	1109-36	VB	7,370	7.3	1.16	2.2	5.81	10.0
		1109-39	AC	9,760	9.6	1.44	5.7	0	- -
		1109-54	AC/ES	11,800	6.1	1.49	4.0	.9	- -
		1109-57	AC/AP	9,500	7.5	1.43	3.6	.01	- -

LF - Longitudinal Flexure

TF - Transverse Flexure

VB - Vacuum Bag

AC - Autoclave

ES - Excess Solvent (1% MEK)

AP - Advanced Prepreg (Air Dry)

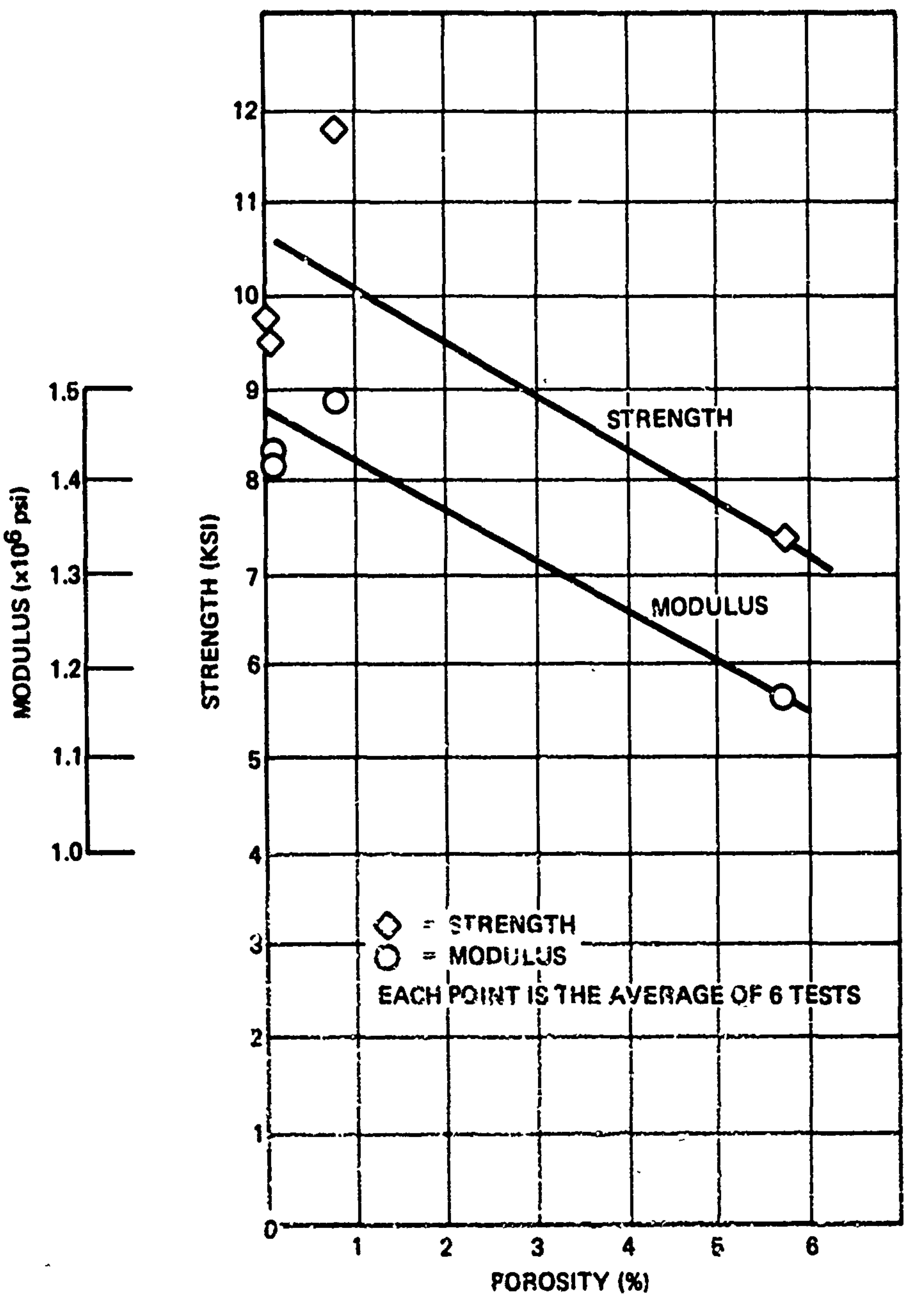


Figure 4.3 TRANSVERSE FLEXURAL PROPERTIES

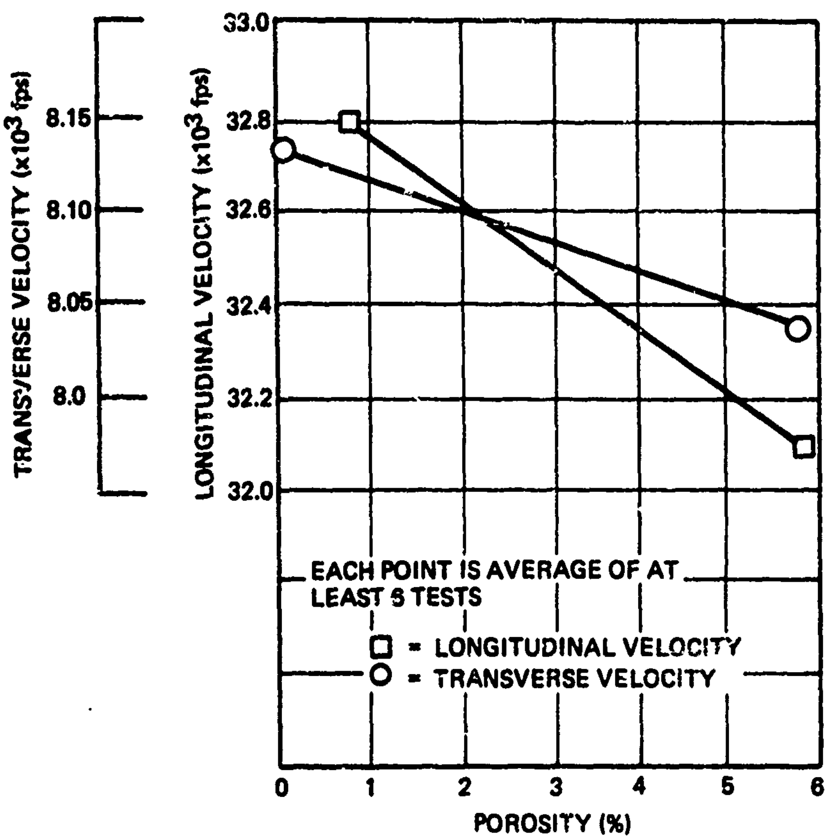


Figure 4.9 VARIATION OF ULTRASONIC VELOCITY WITH POROSITY IN FLEXURE SPECIMENS

The velocity is seen (Figure 4.9) to decrease as the porosity increases and although the data points are statistically different at the 95% confidence level the absolute difference in only 1.2% in the transverse and 2.0% in the longitudinal direction. This is much less sensitive than the mechanical properties which varied by 18% in modulus and 27% in strength for the same porosity variations.

4.5.5 Effect of Porosity on the Tensile Properties of 0/90 Cross Ply Laminates

The tensile data taken in the 0^o, 90^o, and 45^o directions are presented in Table 4.7. For convenience the strength and modulus data are plotted as a function of porosity in Figures 4.10, 4.11, and 4.12. As can be seen the property degradation (both modulus and strength) as a function of porosity is roughly 10% for a 5% void content. This is similar to that found with longitudinal properties in unidirectional material (Figures 4.1 and 4.2).

The stacking sequence is described in Table 2.2 and results in four of the seven plys in the 0^o direction and three in the 90^o direction. Hence the extensional modulus in the 0^o direction should be 4/7 of the longitudinal plus 3/7 of the transverse tensile modulus of a unidirectional composite. From Section 4.5, these values are 20.5 $\times 10^6$ psi and 1.2 $\times 10^6$ psi respectively for a void free material. The predicted modulus therefore is 4/7 x (20.5 $\times 10^6$) plus 3/7 x (1.2 $\times 10^6$) = 12.2 $\times 10^6$ psi. This is very close to the measured modulus of 12.5 $\times 10^6$ psi. Similarly in the 90^o direction the relation becomes 3/7 x (20.5 $\times 10^6$) plus 4/7 x (1.2 $\times 10^6$) = 9.5 which agrees precisely with the measured modulus.

The extensional modulus in the 45^o direction includes shear coupling effects. Tsai's relation for the rotational transformation of extensional stiffness is

$$\frac{1}{E} = \frac{m^4}{E_{11}} + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}}\right) m^2 \quad n^2 + \frac{n^4}{E_{22}}$$

where:

E	is the modulus at the angle θ
E_{11}	is the modulus at 0^o
E_{12}	is the modulus at 90^o
G_{12}	is the shear modulus at 0^o or 90^o
ν_{12}	is the Poisson's ratio on 0^o specimen
n	is the SIN (θ)
m	is the COS (θ)
θ	is the angle from 0^o

TABLE 4.7

EFFECT OF POROSITY ON X PLY LAMINATES

Panel	Orientation	Strength (KSI)	Modulus ($x10^6$ psi)	Porosity (%)	Velocity (fps)	Failure Strain (%)
1109-38	0° Tests	93.4	11.6	4.58	22308	.81
1109-41		98.4	12.5	.34	22736	.80
1109-55		106.0	12.5	1.36		.83
1109-58		92.4	12.4	.40		.81
1109-38	90° Tests	71.9	8.59	4.57	20162	.84
1109-41		92.7	9.59	.61	20129	.99
1109-55		70.4	9.31	.76		.71
1109-58		68.9	9.42	.24		.74
1109-38	45° Tests	18.3	2.06	4.68	- - -	1.7
1109-41		22.9	2.39	.18	- - -	2.3
1109-55		22.8	2.40	.88		2.3
1109-58		25.6	2.36	.21		3.1

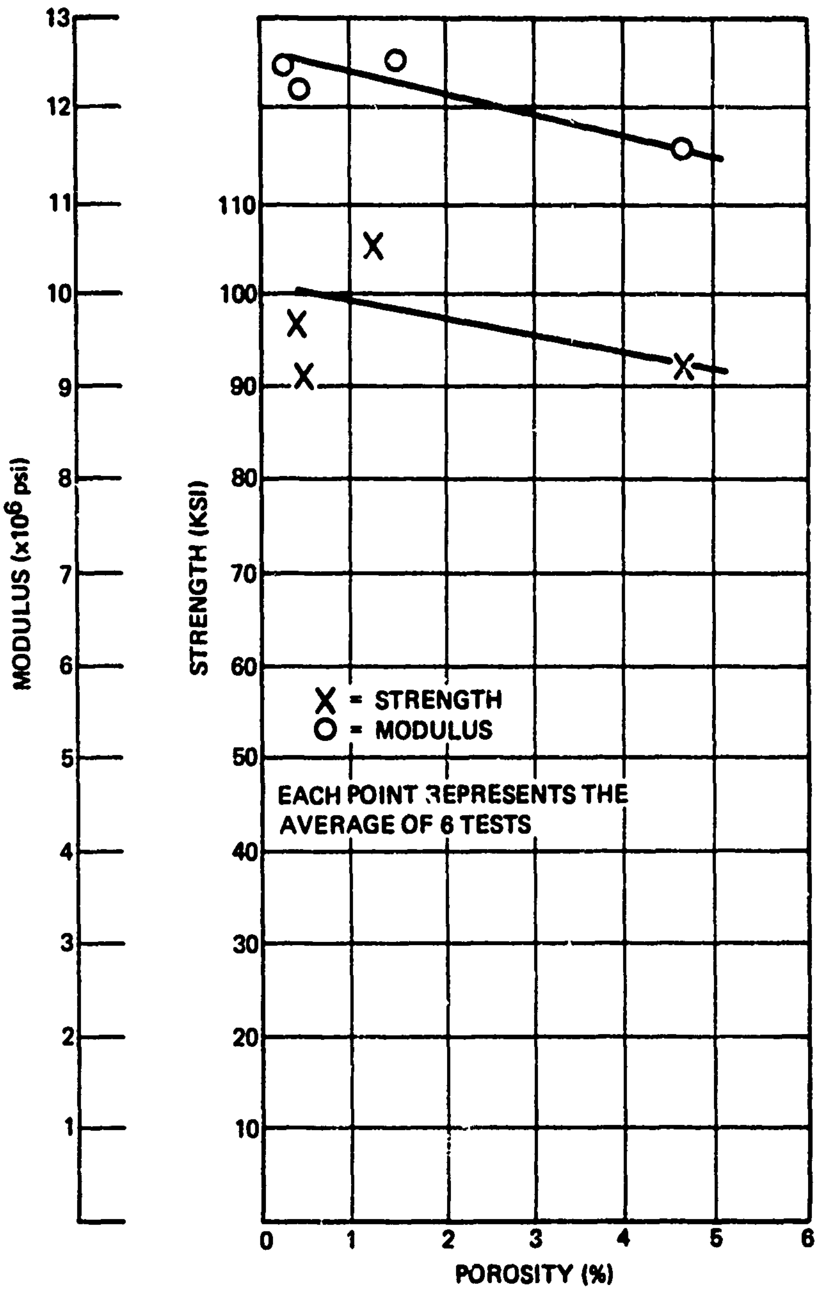


Figure 4.10 0° PROPERTIES OF A CROSS PLY LAMINATE

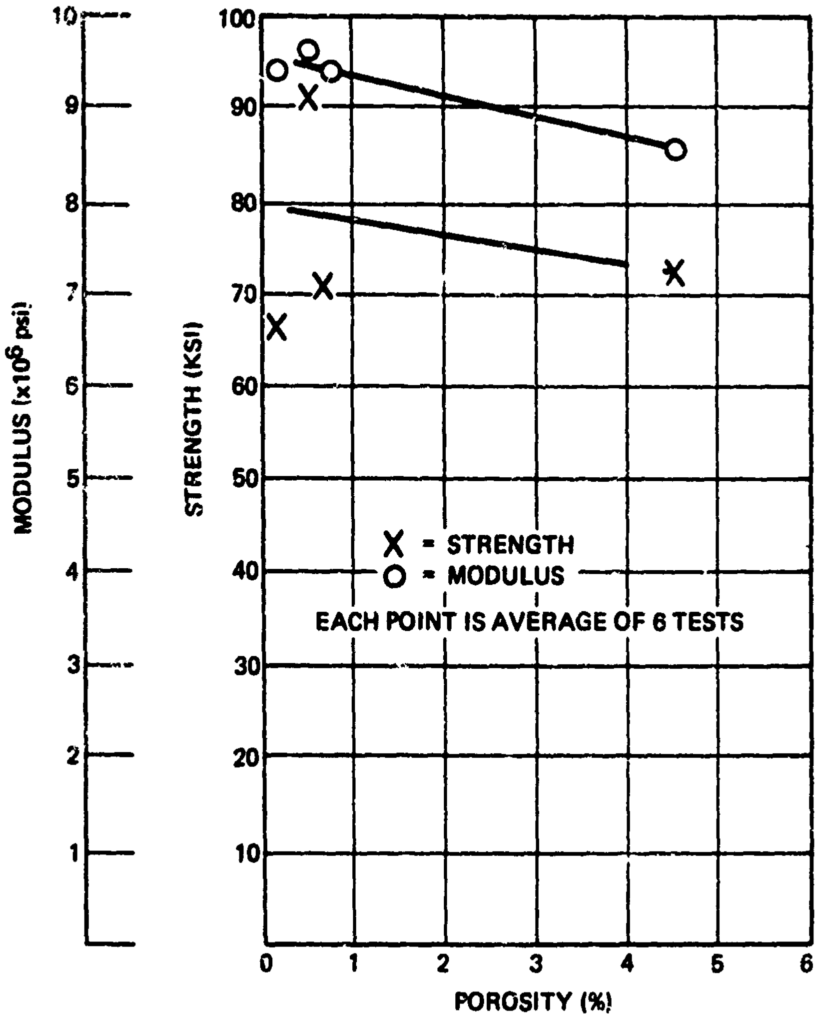


Figure 4.12 90° PROPERTIES OF A CROSS PLY LAMINATE

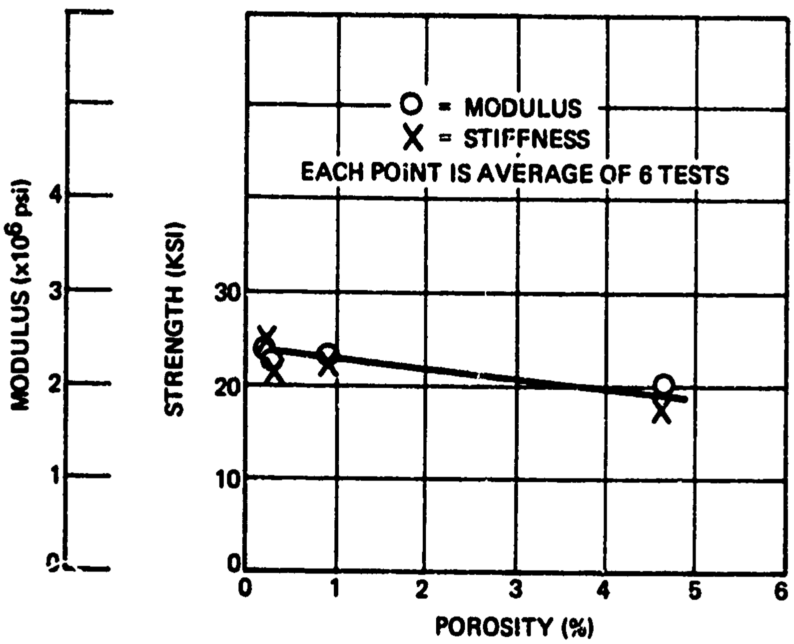


Figure 4.11 45° PROPERTIES OF A CROSS PLY LAMINATE

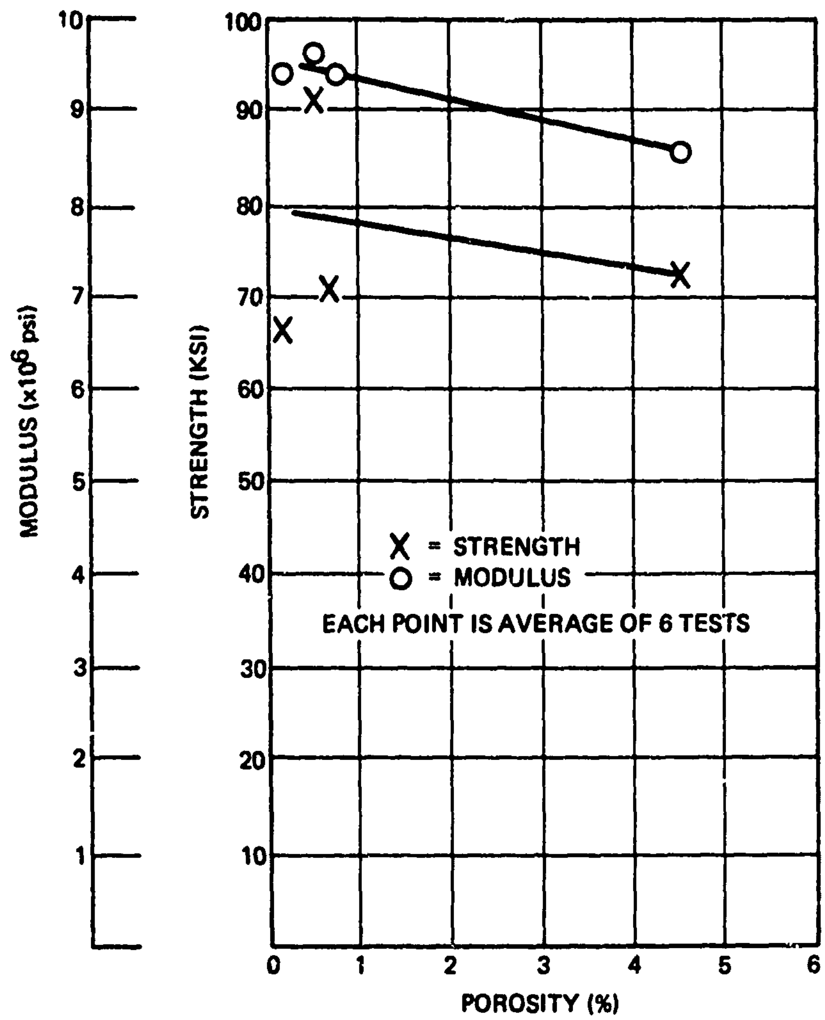


Figure 4.12 90° PROPERTIES OF A CROSS PLY LAMINATE

For a void free material

$$E_{11} = 12.5 \times 10^6 \text{ psi}$$

$$E_{12} = 9.5 \times 10^6 \text{ psi}$$

$$\nu_{12} = 0.3$$

$$G_{12} = .7 \times 10^6 \text{ psi}$$

Using Tsai's (Reference 16) relation the 45^o modulus is 2.5×10^6 psi which compares very favorably with the measured modulus of 2.2×10^6 psi.

The strength in the 0^o and 90^o direction should, to a first approximation be 4/7 and 3/7 respectively of the unidirectional strength, which referring to data in Figure 4.1 is 165 KSI. Hence the 0^o and 90^o strength should be 94 KSI and 71 KSI respectively which compares favorably to the measured values of 100 KSI and 78 KSI.

The ultrasonic velocity data was not plotted as a function of porosity because as was pointed out earlier the means in this data was not statistically different.

5.0 CONCLUSIONS

5.1 Primary Results

1. Both volatile content in the prepreg and molding pressure affect the porosity of Modmor II/5206 laminates.

2. Vacuum bag molding results in a porosity level of approximately 5%.

3. Autoclave molding of standard prepreg results in a laminate having an average void content of 0.50%. When the solvent content in the prepreg is reduced by air drying for 72 hours the laminates have a 0.25% porosity. Increasing the solvent content in the prepreg by 1% by weight results in an average laminate porosity of 1.2%.

4. Short beam shear strength decreases by approximately 10% for each 1% increase in porosity.

5. Flexural strength decreases by approximately 5% for each 1% increase in porosity. This is true for both longitudinal and transverse properties. The moduli decrease by a lesser amount.

6. Compression strength decreases by approximately 5% for each 1% increase in porosity.

7. The longitudinal and transverse tensile strength and modulus decrease by approximately 2% for each 1% increase in porosity. This holds for both the unidirectional and 0/90° cross ply laminates studied.

8. Ultrasonic C-scan attenuation techniques are well suited for porosity determinations. The technique is sensitive enough to detect variations of the order of $\frac{1}{2}$% porosity and can be used with both unidirectional and cross ply laminates.

9. Ultrasonic velocity measurements are not well suite for use in assessing the void content in these composites. It is only 1/10th as sensitive as the mechanical properties are to porosity in the unidirectional composite and is totally insensitive to porosity in the 0/90° cross ply laminates.

5.2 Supplementary Results

1. Porosity in Modmor/5206, resulting from either low molding pressure or high volatile content in the resin, occurs premarily between plys.

2. Water absorption can be used to accurately determine porosity.

3. A water boil and subsequent dry cycle at 212°F for extended periods (up to 300 hours for each event) has no detrimental effect upon the mechanical properties of this composite.

4. Several visual prepreg variations such as wavy tows, a whiskered surface, and an uneven distribution of resin have no effect on the mechanical properties of the laminate.

6.0 SUGGESTION FOR FUTURE RESEARCH

The interlaminar shear strength decreased significantly with small amounts of porosity. Based upon this finding the lap shear strength of adhesively bonded joints is also expected to be significantly altered by the presence of voids. Since the optimum joining technique for fiber reinforced plastics is adhesive bonding, a study of the effects of defects on adhesive joints would be of extreme importance.

It was also found that the three prepreg variations observed namely, misaligned tows, a whiskered prepreg surface and non-uniform distribution of resin had no effect on the observed mechanical properties. The same type of variations, if they were either more severe or more abundant, are expected to influence the mechanical properties. A study identifying the kind of prepreg defect, its severity and its abundance would be useful in determing acceptance criteria for prepreg and if certain kinds of defects could be tolerated the cost of the material would decrease due to less stringent manufacturing controls.

Prior studies have demonstrated the superiority of autoclave molding. It was shown, however, that by reducing the volitale content in the resin below its normal level an even less porous laminate could be produced. This slight reduction in porosity has no effect on the static properties but might improve the fatigue strength due to the decreased number of initial defect sites. In fact the water absorption technique which was used for porosity determination in the present study has been employed by F. J. McGarry to study microcracking in glass reinforced plastics subjected to cyclic loads and could be used as an aid in studying fatigue phenomena in graphite/epoxies.

Finally, a study directed towards the effects of gross flaws such as delaminations, gouges and through cracks an the residual load carrying capability of fiber reinforced composites appears to be appropriate at this time. Such an investigation should include not only techniques for flaw detection but should be aimed at determining when a component is no longer air worthy.

7.0 REFERENCES

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8.0 APPENDIX

A. Effect of Prepreg Variables on the Tensile Properties of Unidirectional Laminates

B. Effect of Water Boil/Dry Cycle on the Mechanical Properties of Unidirectional Laminates

C. Void Characterization Studies

D. C-scans of Test Panels

E. Ultrasonic Velocity Data

F. Mechanical Properties as a Function of Porosity

APPENDIX A

EFFECT OF PREPREG VARIABLES ON TENSILE PROPERTIES OF UNIDIRECTIONAL LAMINATES

MECHANICAL PROPERTIES
1109-65 0^{o} 6 PLY AUTOCLAVE - FUZZY PREPREG

Longitudinal Tension (LT)				Transverse Tension (TT)			
Specimen Number	Strength (psi)	Modulus (x10^{-6} psi)	Strain to Failure %	Specimen Number	Strength (psi)	Modulus (x10^{-6} psi)	Strain to Failure %
LT 7	155,000	19.0	0.82	TT 1	6440	1.22	0.52
8	164,000	19.6	0.82	2	6340	1.21	0.52
9	122,000	18.8	0.65	3	5930	1.13	0.52
10	143,000	19.5	0.73	4	6200	1.13	0.54
11	167,000	19.6	0.83	5	5350	1.12	0.45
12	154,000	18.5	0.81	6	4620	1.16	0.39
13	144,000	18.4	0.78				
14	155,000	19.3	0.80				
15	166,000	19.8	0.82				
16	150,000	19.1	0.77				
17	116,000	16.2	0.70				
Average	149,000	18.9	0.78	Average	5810	1.16	0.49
Cv	11.25	5.30	7.50	Cv	1.21	5.75	11.80

MECHANICAL PROPERTIES
1109-63 0^{o} 6 PLY AUTOCLAVE - DRY PREPREG

Longitudinal Tension (LT)				Transverse Tension (TT)			
Specimen Number	Strength (psi)	Modulus (x10^{-6} psi)	Strain to Failure %	Specimen Number	Strength (psi)	Modulus (x10^{-6} psi)	Strain to Failure %
LT 8	144,000	18.1	0.76	TT 1	5510	1.21	0.45
9	115,000	18.5	0.62	2	5620	1.20	0.46
10	174,000	18.5	0.93	3	5490	1.19	0.48
11	160,000	18.2	0.86	4	5340	1.19	0.47
12	167,000	18.6	0.86	5	4170	1.16	0.36
13	163,000	18.5	0.83	6	5020	1.22	0.42
14	169,000	18.4	0.88				
15	161,000	18.4	0.86				
16	183,000	18.7	0.95				
17	153,000	18.7	0.84				
18	133,000	18.3	0.71				
Average	157,000	18.4	0.83	Average	5190	1.20	0.44
Cv	12.4	1.04	11.6	Cv	10.4	1.73	10.06

MECHANICAL PROPERTIES
1109-66 0° 6 PLY AUTOCLAVE - STANDARD PREPREG

Longitudinal Tension (LT)				Transverse Tension (TT)			
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure %	Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure %
LT 7	151,000	13.3	0.81	TT 1	5270	1.25	0.42
8	174,000	19.9	0.85	2	5570	1.32	0.43
9	115,000	19.1	0.60	3		1.33	0.49
10	131,000	19.4	0.67	4	5980	1.35	0.46
11	158,000	19.0	0.80	5	6270	1.28	- -
12	168,000	18.9	0.87	6	6000	1.35	0.46
13	164,000	19.4	0.82				
14	157,000	20.2	0.78				
15	115,000	20.0	0.57				
16	144,000	20.3	0.69				
17	134,000	18.2	0.74				
Average	146,000	18.9	0.75	Average	5910	1.31	0.45
Cv	14.0	10.3	13.4	Cv	7.20	3.07	6.16

MECHANICAL PROPERTIES
1109-64 0° 6 PLY AUTOCLAVE, WAVY PREPREG

Longitudinal Tension (LT)				Transverse Tension (TT)			
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure %	Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure %
LT 8	163,000	18.2	0.89	TT 1	6065	1.24	0.48
9	136,000	19.0	0.69	2	5830	1.23	0.47
10	163,000	18.6	0.85	3	5880	1.24	0.49
11	137,000	18.3	0.73	4	5650	1.31	0.43
12	195,000	20.8	0.90	5	5210	1.25	0.43
13	169,000	19.9	0.81	6	5960	1.23	0.48
14	181,000	20.2	0.86				
15	180,000	19.7	0.87				
16	185,000	21.1	0.85				
17	171,000	19.9	0.82				
18	119,000	19.3	0.62				
Average	164,000	19.5	0.81	Average	5760	1.25	0.46
Cv	14.38	4.9	11.0	Cv	5.25	2.42	5.78

APPENDIX B

EFFECT OF WATER BOIL/DRY CYCLE ON MECHANICAL PROPERTIES

1. Data From Panel 1109-59
2. Data From Panel 1109-62

EFFECT OF WATER BOIL/DRY CYCLE ON MECHANICAL PROPERTIES
PANEL 1109-59 12 PLY, 0°, AUTOCLAVE MOLDED

A. Compression				B. Short Beam Shear			
Control Specimens		Water Boil/Dry Specimens		Control Specimen		Water Boil/Dry Specimens	
Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)
1	141	2	152	1	16.4	2	16.2
3	158	4	160	3	16.3	4	16.6
5	143	6	140	5	16.7	6	16.2
7	151	8	138	7	15.8	8	16.3
9	153	10	156	9	16.1	10	16.2
11	136	12	153	11	16.3	12	16.5
13	130	14	108*	13	16.0	14	15.9
15	151	16	141	15	15.0	16	16.6
17	134	18	144	17	16.4	18	16.6
19	140	20	129	19	16.4	20	16.4
21	143	22	122	21	16.6	22	16.2
23	144	24	121	23	15.7	24	16.9
25	139	26	128	25	16.3	26	16.4
27	127	28	125	27	17.8	28	16.1
29	137	30	112	29	16.1	30	14.5
Average	141	Average	137.2	Average	16.3	Average	16.2
Cv	5.9%	Cv	10.3%	Cv	2.5%	Cv	3.2%

*Severe Surface Defect

PANEL 1109-59 CONTINUED

C. Longitudinal Flexure

Control Specimens			Water Boil/Dry Specimens		
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)
1	259	21.8	2	239	21.1
3	254	21.0	4	262	21.1
5	241	21.7	6	251	21.0
7	241	20.7	8	244	20.7
9	245	20.9	10	270	21.0
11	213	21.1	12	253	20.8
13	250	19.9	14	258	20.8
15	234	21.1		--	--
Average	242	21.0	Average	254	20.9
Cv	5.5%	2.8%	Cv	3.8%	0.7%

D. Transverse Flexure

Control Specimens			Water Boil/Dry Specimens		
Specimen Number	Strength (KSI	Modulus ($x10^{-6}$ psi)	Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)
1	14.1	1.49	2	11.2	1.45
3	13.3	1.49	4	9.80	1.38
5	14.9	1.42	6	9.72	1.34
7	13.7	1.44	8	10.8	1.23
9	13.2	1.49	10	11.5	1.29
11	12.8	1.43	12	10.9	1.40
13	12.1	1.42	14	11.8	1.40
15	11.7	1.38			
Average	13.2	1.45	Average	10.8	1.36
Cv	7.3%	2.8%	Cv	6.8%	5.5%

EFFECT OF WATER BOIL/DRY CYCLE ON MECHANICAL PROPERTIES
PANEL 1109-62 12 PLY, 0° AUTOCLAVE MOLDED

A. Compression				B. Short Beam Shear			
Control Specimens		Water Boil/Dry Specimens		Control Specimens		Water Boil/Dry Specimens	
Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)	Specimen Number	Strength (KSI)
1	155	2	145	1	16.8	2	16.2
3	145	4	137	3	15.7	4	16.7
5	142	6	143	5	16.6	6	16.7
7	137	8	127	7	16.3	8	16.5
9	140	10	132	9	16.0	10	16.5
11	123	12	108	11	15.9	12	16.4
13	125	14	114	13	16.6	14	16.4
15	141	16	143	15	16.7	16	16.3
17	123	18	129	17	16.7	18	15.8
19	126	20	150	19	16.7	20	16.4
21	111	21	142	21	16.2	22	16.4
23	131	24	134	23	16.8	24	16.5
25	136	26	133	25	16.6	26	15.5
27	155	28	135	27	16.3	28	16.0
29	113	30	126	29	16.2	30	15.0
Average	133	Average	133	Average	16.3	Average	16.2
Cv	9.7%	Cv	8.2%	Cv	2.0%	Cv	2.7%

1109-62 CONTINUED

C. Longitudinal Flexure					
Control Specimens			Water Boil/Dry Specimens		
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)
1	259	21.5	2	252	21.2
3	278	24.7	4	245	20.8
5	239	20.2	6	229	20.7
7	230	20.8	8	253	21.2
9	233	21.1	10	236	20.7
11	241	21.6	12	256	21.2
13	244	22.2	14	243	21.2
15	252	21.3		--	--
Average	247	21.7	Average	245	21.0
Cv	5.9%	6.2%	Cv	3.7%	1.2%

D. Transverse Flexure					
Control Specimens			Water Boil/Dry Specimens		
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)
1	14.6	1.38	2	11.7	1.38
3	14.4	1.38	4	11.1	1.42
5	9.38*	1.38	6	12.5	1.41
7	12.4	1.42	8	11.6	1.40
9	13.4	1.45	10	12.5	1.44
11	12.7	1.46	12	11.3	1.46
13	12.2	1.53	14	12.5	1.46
15	12.9	1.46	16	13.5	1.47
Average	12.7	1.43	Average	12.1	1.43
Cv	11.8%	3.7%	Cv	6.2%	2.3%

*Not included in average

APPENDIX C

VOID CHARACTERIZATION STUDIES

POROSITY DATA

Part I - Void Characterization Specimens

Data is included on all void characterization specimens. The data for specimens from each panel is presented in discrete packages and includes the following:

a) Water absorption curves for all specimens from a panel.
b) The 10x micrographs showing the porosity of each specimen.
c) A summary of porosity determined by both the metallographic point count technique and the water absorption method.

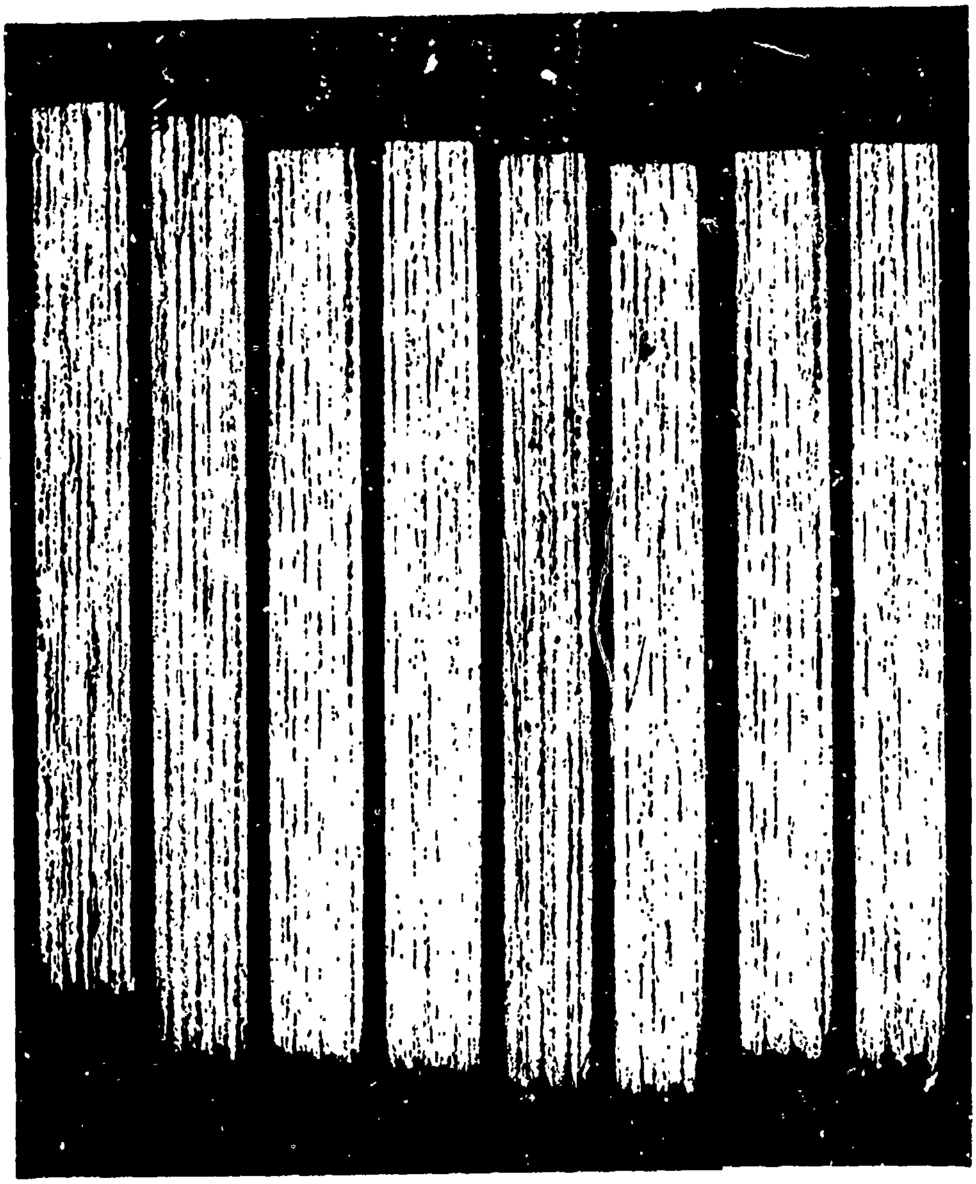
The data packages are in the order listed below:

Data Order	Panel	Notes
1	1109-38	Vacuum Bag
2	1109-36	Vacuum Bag
3	1109-37	Vacuum Bag
4	1109-41	Autoclave Molded
5	1109-39	Autoclave Molded
6	1109-40	Autoclave Molded
7	1109-55	Autoclave/Excess Solven
8	1109-54	Autoclave/Excess Solven
9	1109-53	Autoclave/Excess Solven
10	1109-58	Autoclave/Advanced Prepreg
11	1109-57	Autoclave/Advanced Prepreg
12	1109-56	Autoclave/Advanced Prepreg

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-38 WB 0/90 7 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
19	2.0*	3.0	3.6
20	2.6	3.9	9.6
21	2.15	3.2	1.7
22	2.1	3.1	3.5
23	2.7	4.0	6.6
24	2.2	3.3	7.6
25	2.7	4.0	2.5
26	3.2	4.8	7.2
		$\bar{X}$ 3.66	$\bar{X}$ 5.28

*Not equilibrium



19 20 21 22 23 24 25 26

(Specimen Width = .050 Inches)

Panel 1109-38								
Specimen No.	19	20	21	22	23	24	25	26
Void Content* (%)	3.6	9.6	1.7	3.5	6.6	7.6	2.5	7.2

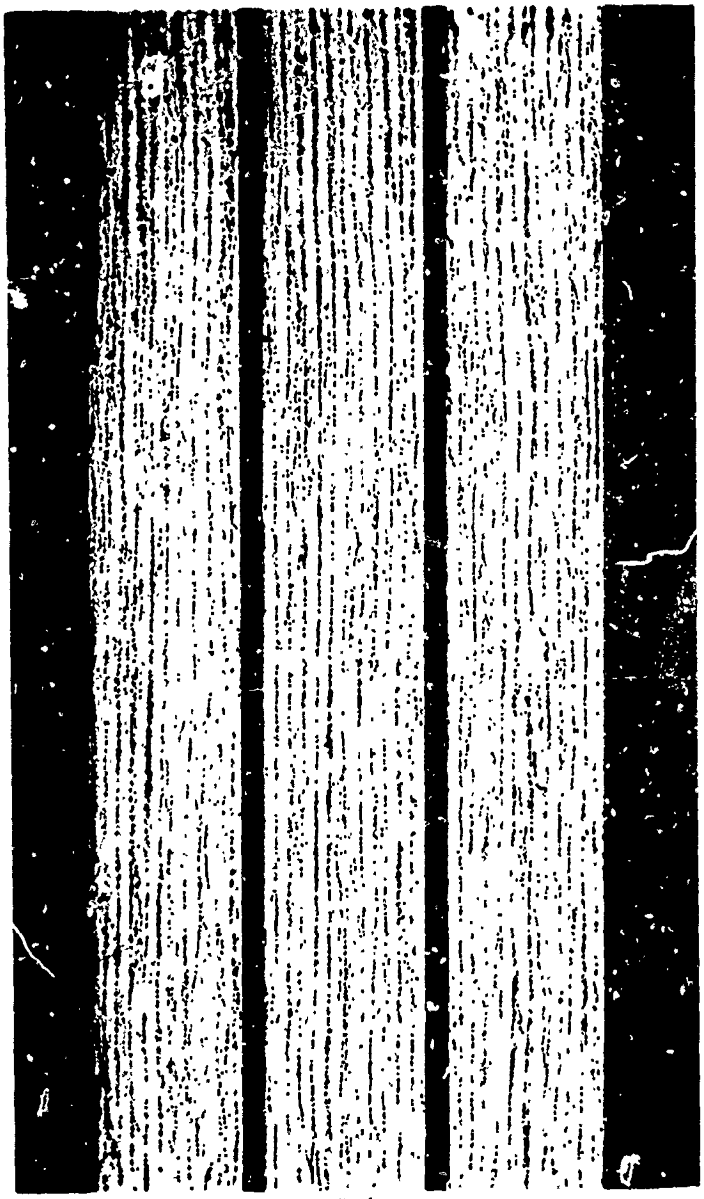
*From IMANCO

FIGURE 2b PHOTOMICROGRAPH OF THE VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-38

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-36 VB 0^{o} 12 PLY

Specimen Number	Water Absorption: Excess Moisture (%)	Water Absorption: Porosity (%)	Point Count: Porosity (%)
17	3.2*	4.8	9.9
18	3.5*	5.2	9.4
19	3.6*	5.4	6.1
		$\bar{X}$ 5.1	$\bar{X}$ 8.4

*Not equilibrium



1109-36

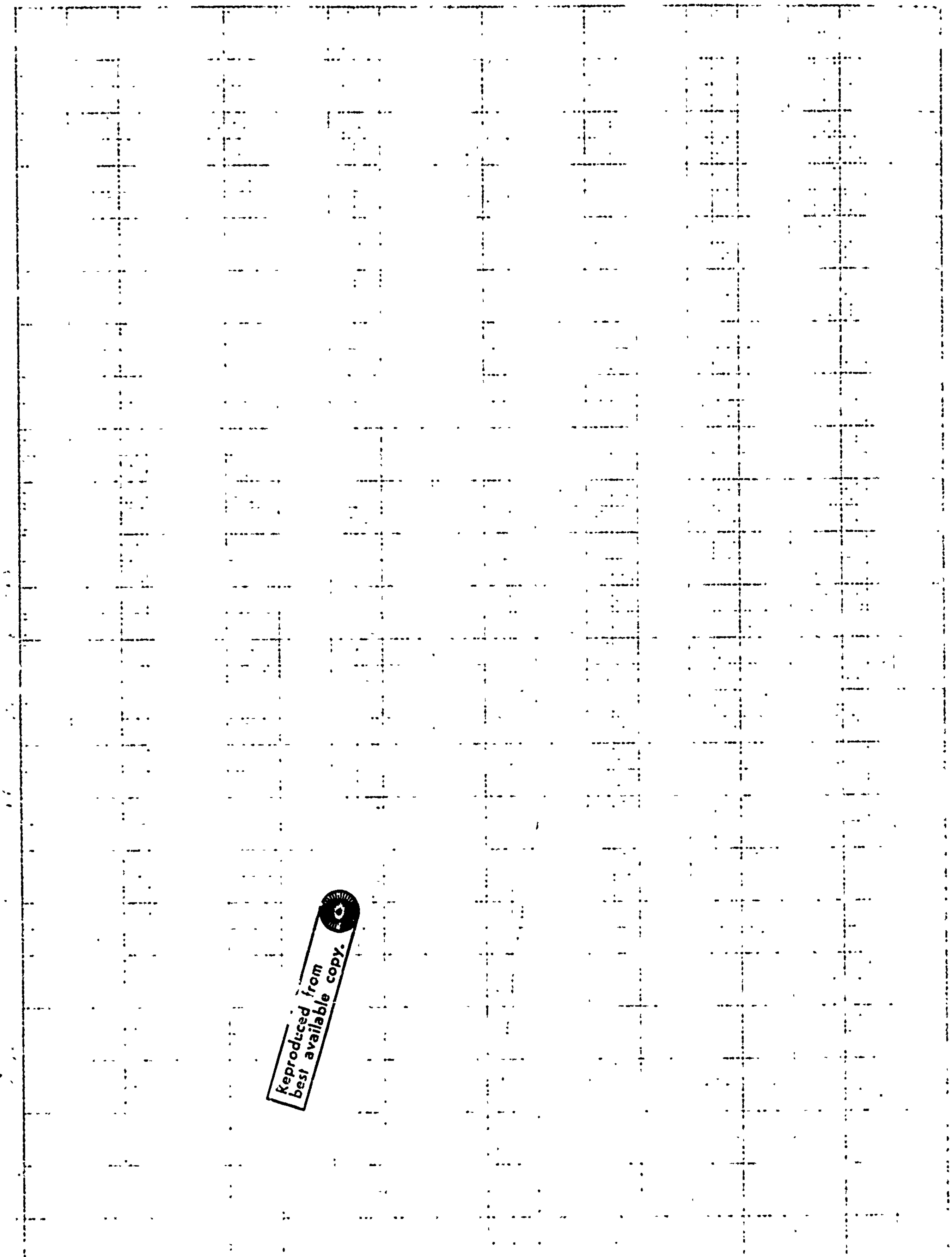
17 18 19

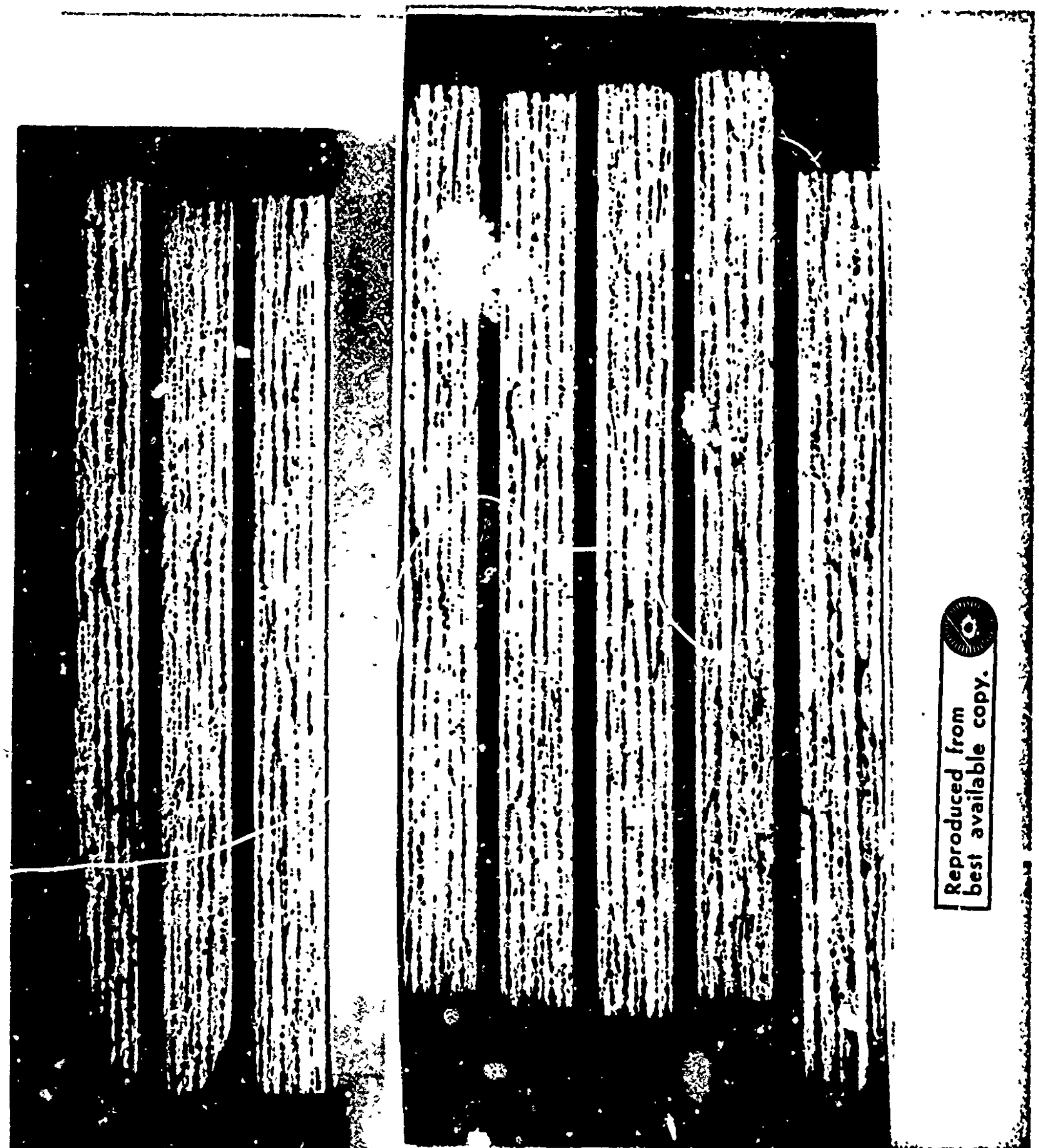
(Specimen Width = .090 Inches)

Panel 1109-38			
Specimen No.	17	18	19
Void Content* (%)	9.9	9.4	6.1

*From IMANCO

FIGURE 3b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMEN FROM PANEL 1109-38





1109-37 1109-37

A B C D E F G H

(Specimen Width = .043 Inches)

Panel 1109-37								
Specimen	A	B	C	D	E	F	G	H
Void Content* (%)	5.1	7.3	5.5	7.7	4.6	6.7	8.5	14.6

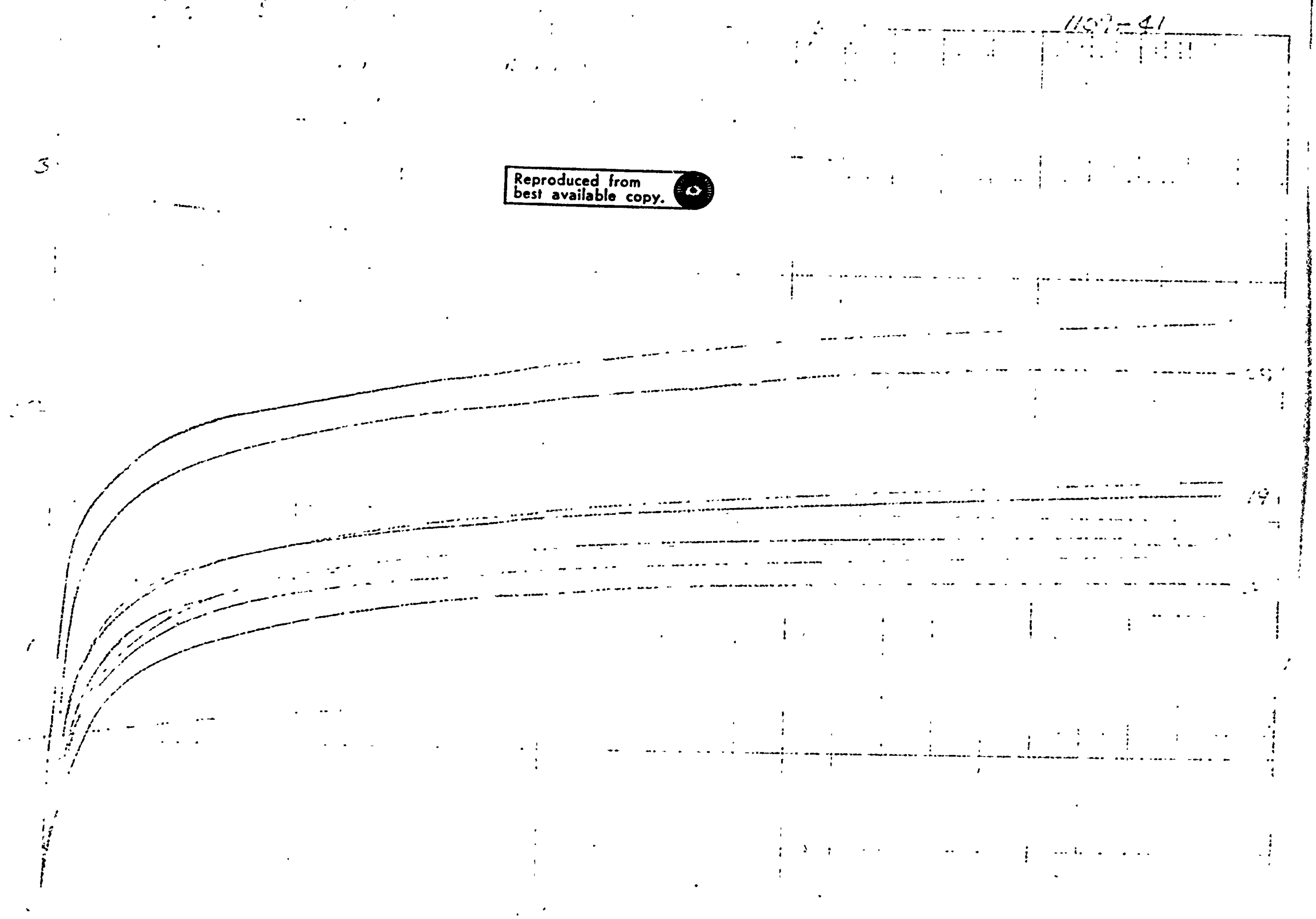
*From IMANCO

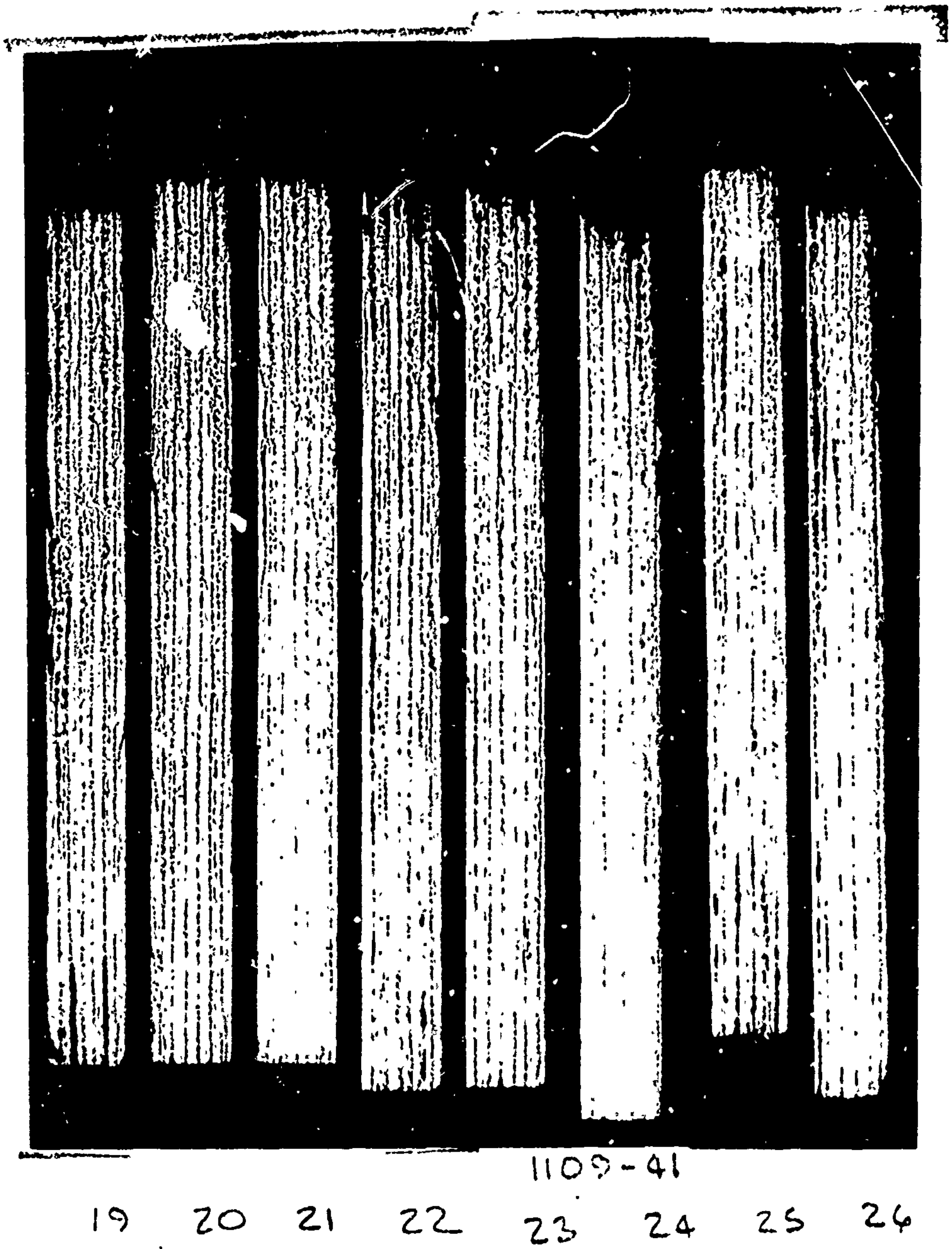
FIGURE 4b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-37

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-37 VS 0° 6 PLY

	Water Absorption*		Point Count
Specimen Number	Excess* Moisture (%)	Porosity (%)	Porosity (%)
A	3.2	4.8	5.1
B	3.1	4.6	7.3
C	3.4	5.1	5.5
D	3.4	5.1	7.7
E	3.5	5.2	4.6
F	3.4	5.1	6.7
G	4.2	6.3	8.5
H	4.8	7.2	14.6
		$\bar{X}$ 5.42	$\bar{X}$ 7.50

*Not equilibrium





Magnification 10X

Panel 1109-41								
Specimen No.	19	20	21	22	23	24	25	26
Void Content* (%)	1.1	—	--	0.9	2.0	1.4	2.1	1.8

*From IMANCO

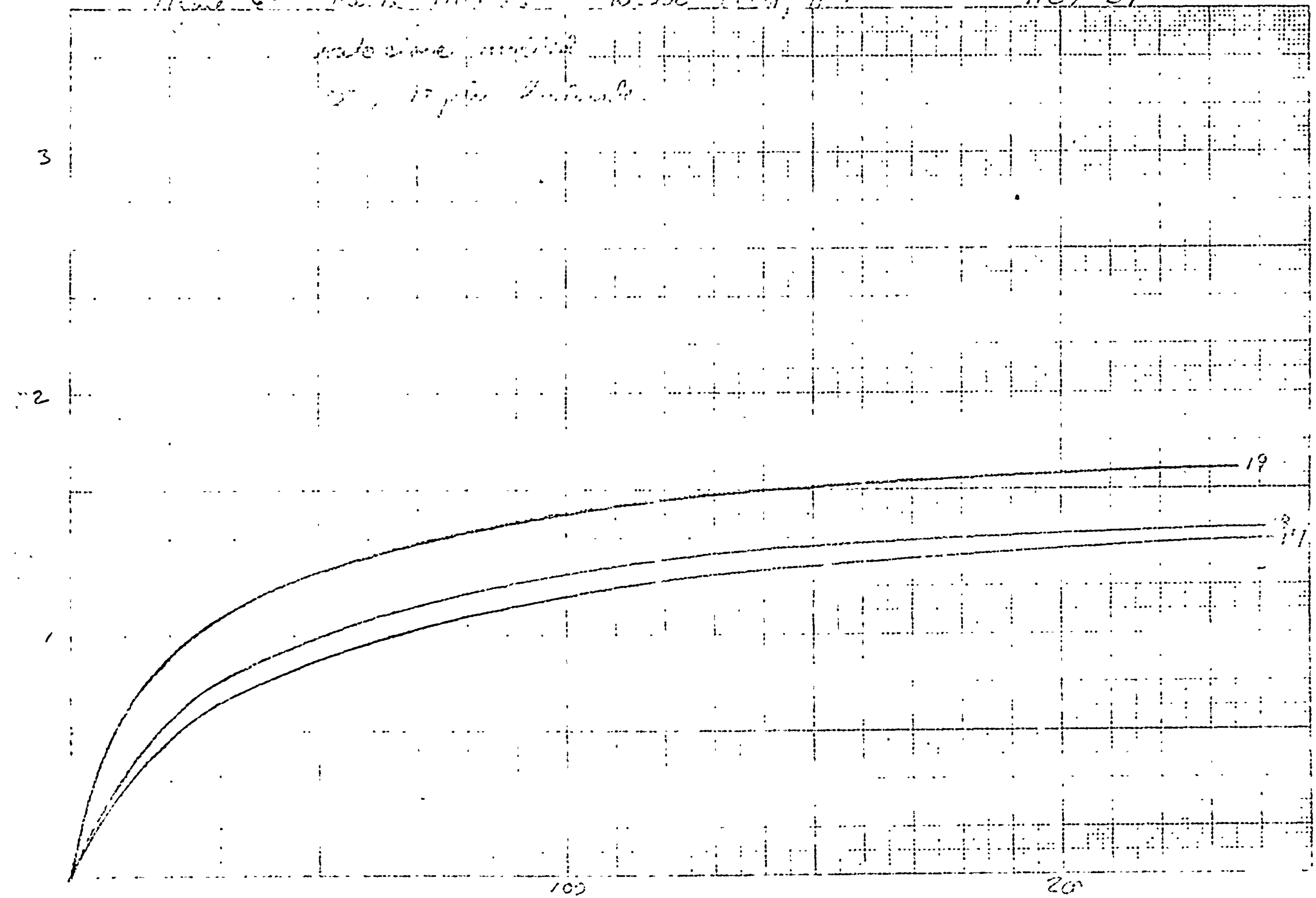
FIGURE 5b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-41

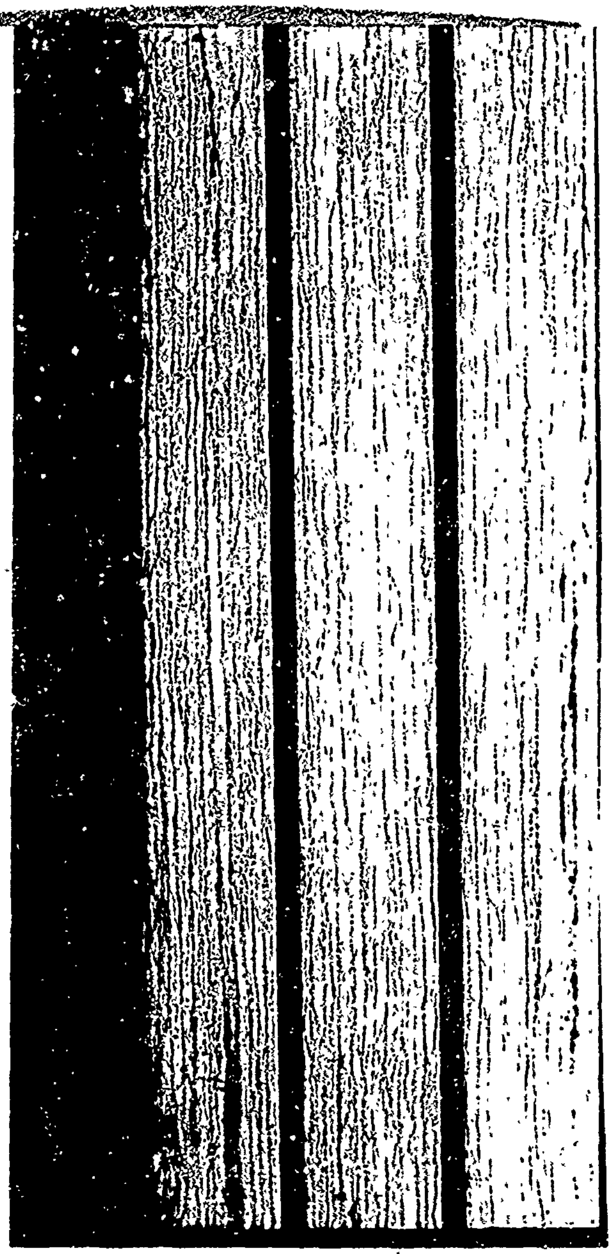
SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-41 AC 0/90 7 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
19	.36	.54	1.1
20	.18	.27	- -
21	.1	.15	- -
22	.44	.65	0.9
23	.16	.24	2.0
24	0	0	1.4
25	.90	1.35	2.4
26	1.10	1.65	1.8
		$\bar{X}$ .61	$\bar{X}$ 1.20

Figure 6

1109-39





Magnification 10X

Panel 1109-39			
Specimen No.	17	18	19
Void Content* (%)	1.0	- -	0.2

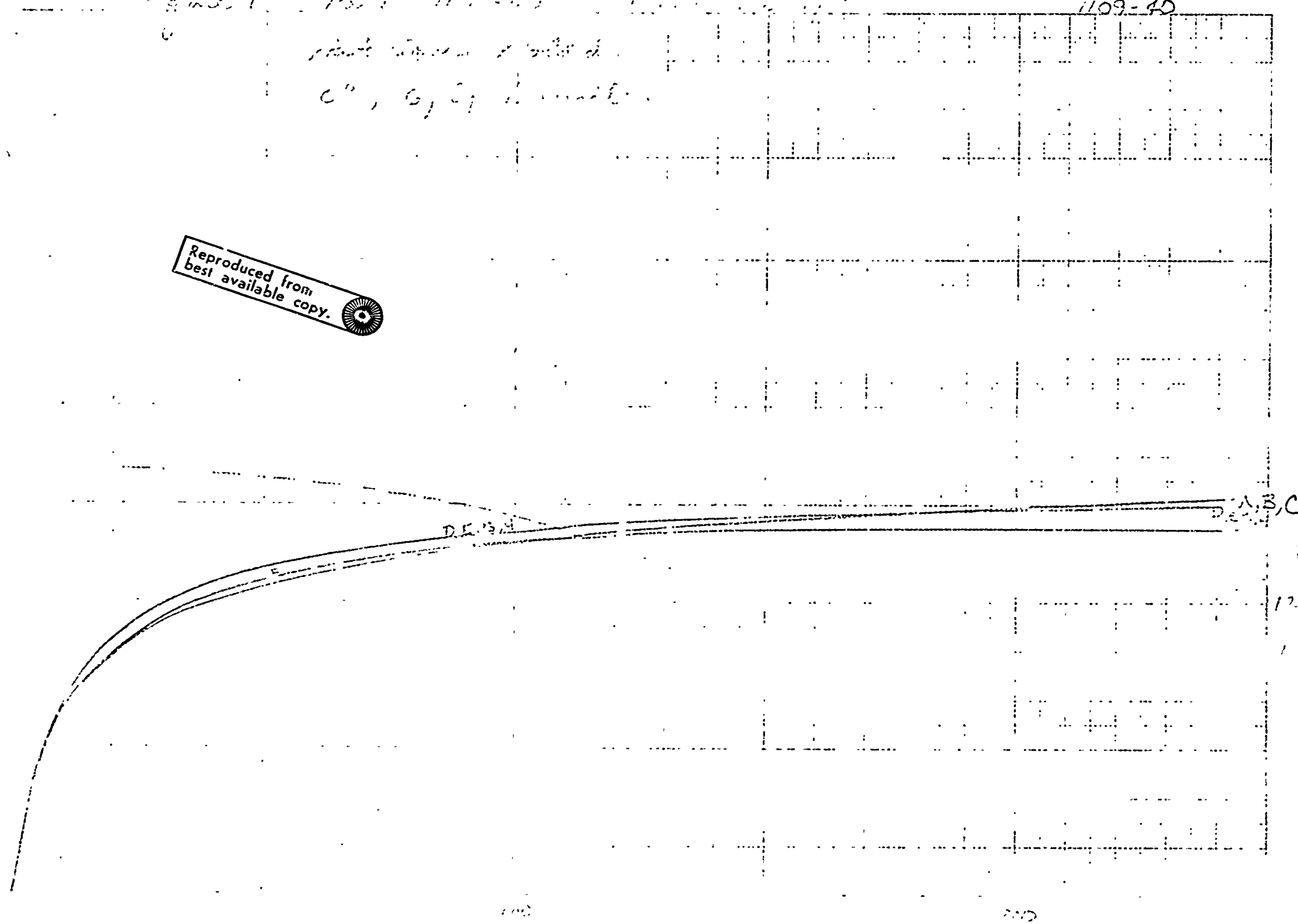
*From IMANCO

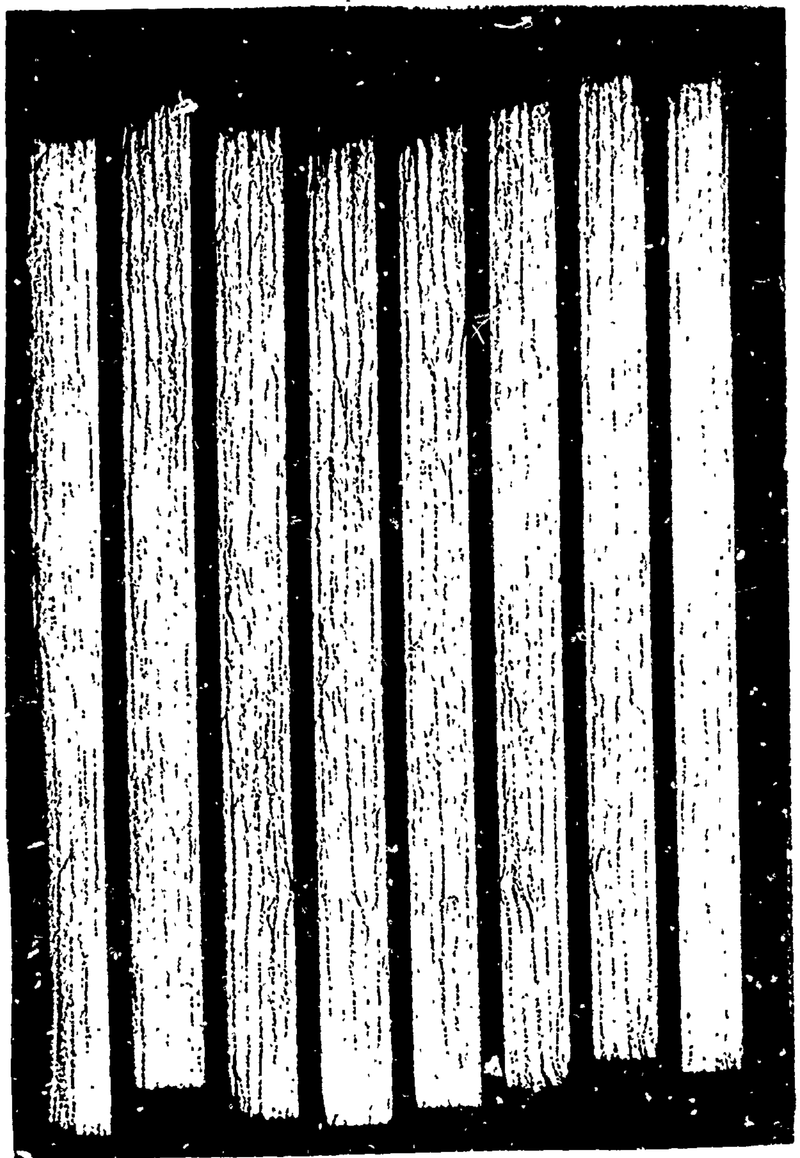
FIGURE 6b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-39

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-39 AC 0° 12 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
17	.12	.18	1.0
18	.18	.27	0
19	.42	.63	.2
		$\bar{X}$ .36	$\bar{X}$ .40

Figure 7





1109-40

A B C D E F G H

Magnification 10X

Panel 1109-40								
Specimen No.	A	B	C	D	E	F	G	H
Void Content* (%)	-	-	-	.4	.4	-	-	-

*From IMANCO

FIGURE 7b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-40

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL [illegible]109-40 AC 0° 6 PLY

Specimen Number	Water Absorption: Excess Moisture (%)	Water Absorption: Porosity (%)	Point Count: Porosity (%)
A	36	.54	0
B	36	.54	0
C	36	.54	0
D	34	.51	.4
E	34	.51	.4
F	.24	.36	0
G	34	.51	0
H	34	.51	0
		$\bar{X}$ .50	$\bar{X}$ .1

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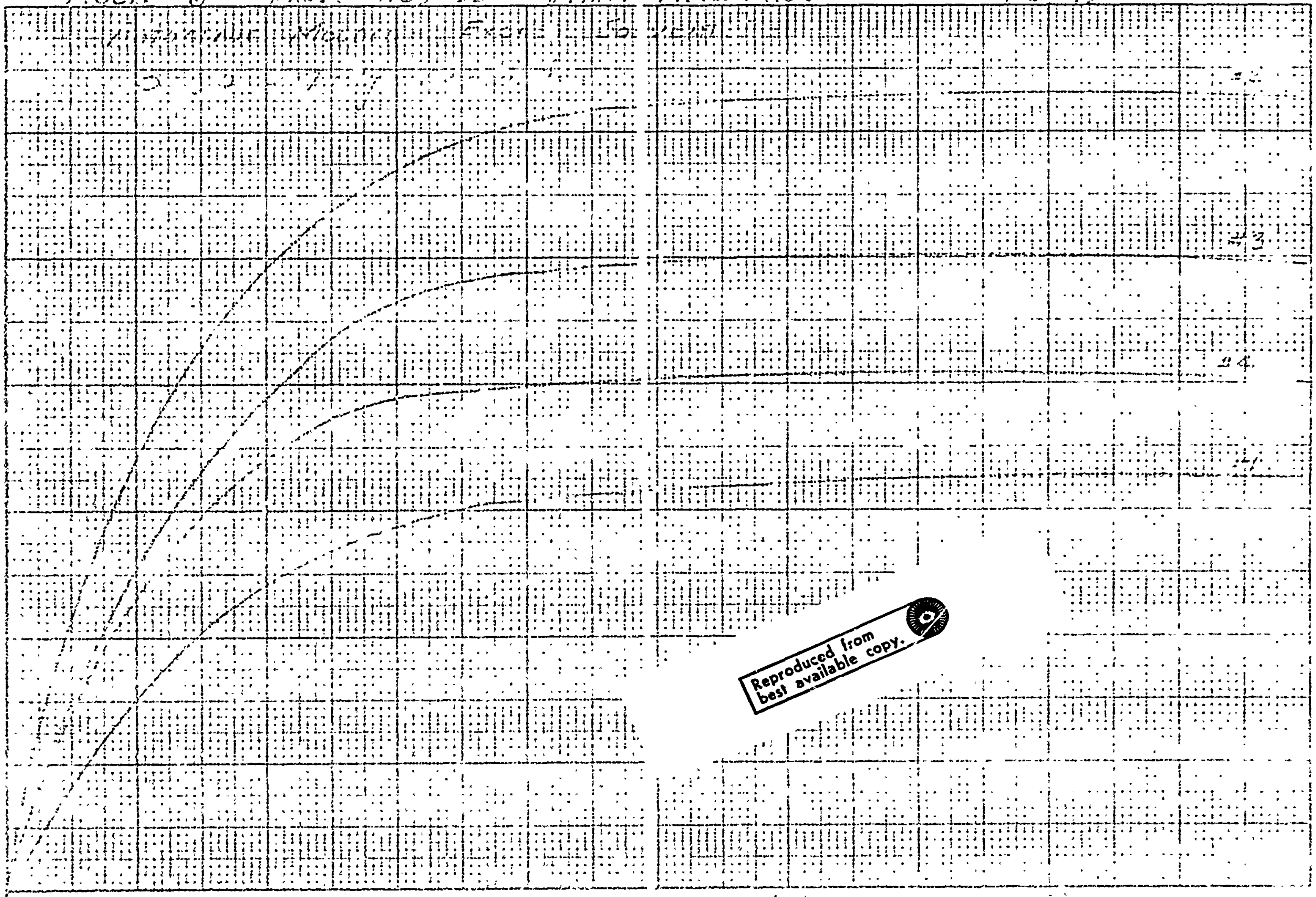
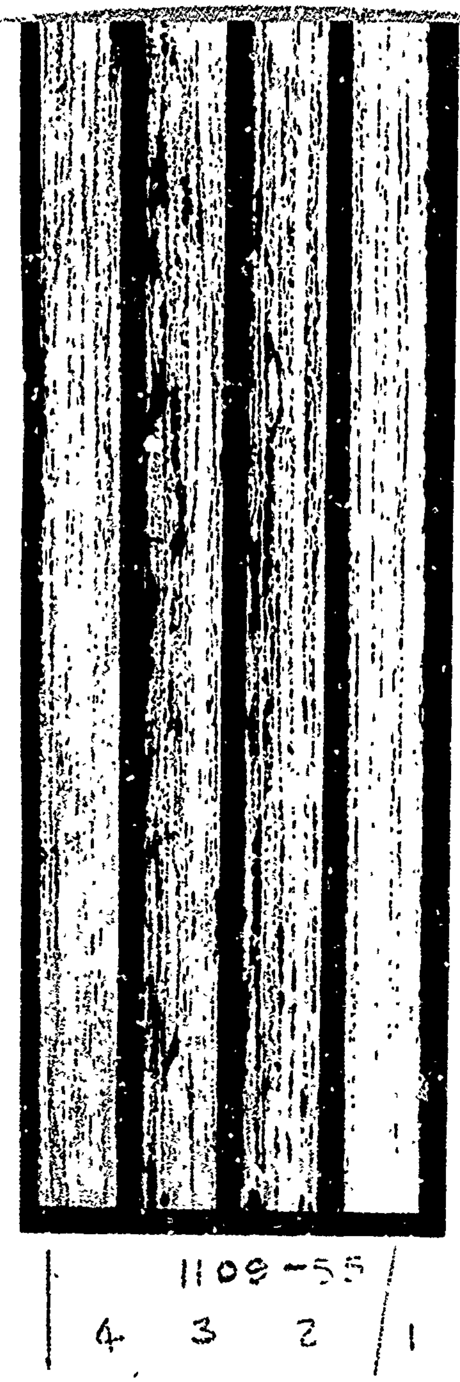
Figure 8 - Panel 1103-55 · Water Absorption





Magnification 10X

Panel 1109-55				
Specimen No.	1	2	3	5
Void Content (%)	.31	4.8	4.1	1.9

FIGURE 8b PHOTOMICROGRAPH OF VOID CHARACTERIZATION SPECIMENS FROM PANEL 1109-55

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-55 AC/ES 0/90 7 PLY

	Water Absorption		Point Count	
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)	C-Scan
1	.35	0.53	.31	Low
2	2.0	3.0	4.8	High
3	1.25	1.9	4.1	High
4	.75	1.1	1.9	Low
		$\bar{X}$ 1.63	$\bar{X}$ 2.77	

NO. 340-16 DIETZGEN GRAPH PAPER
16 X 16 PER INCH

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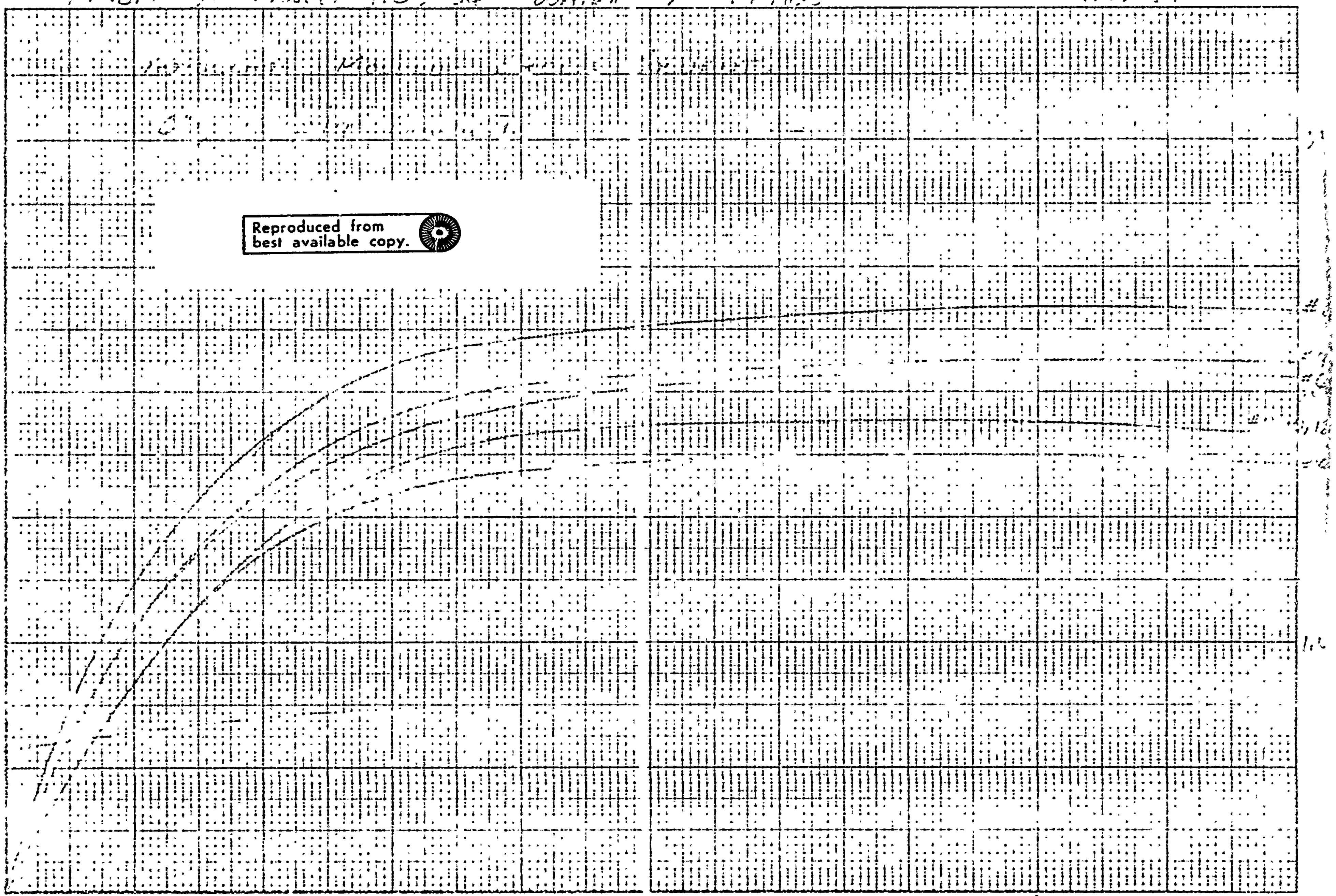
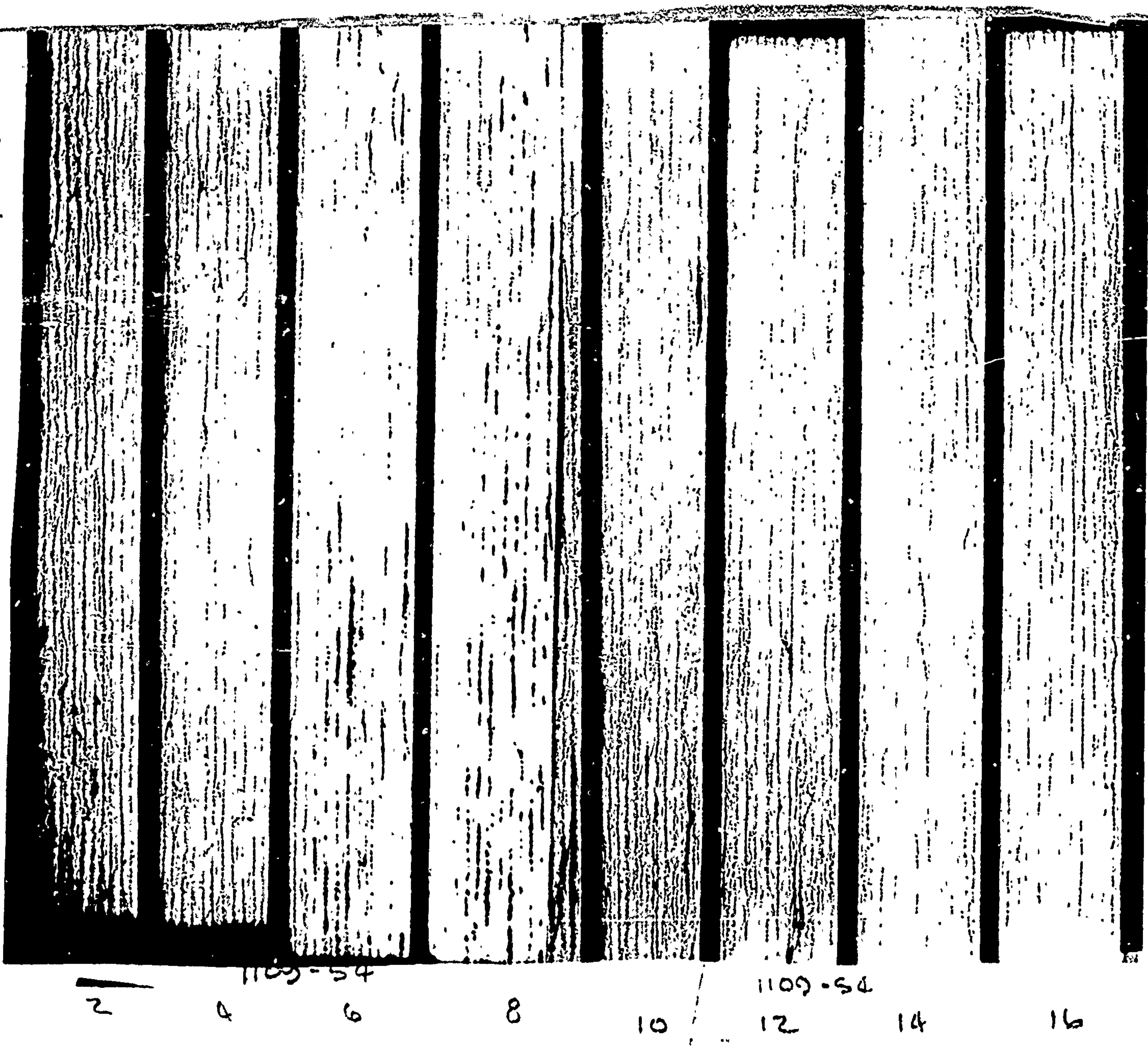
FIGURE 9 - PANEL 1102-54 - WATER ABSORPTION





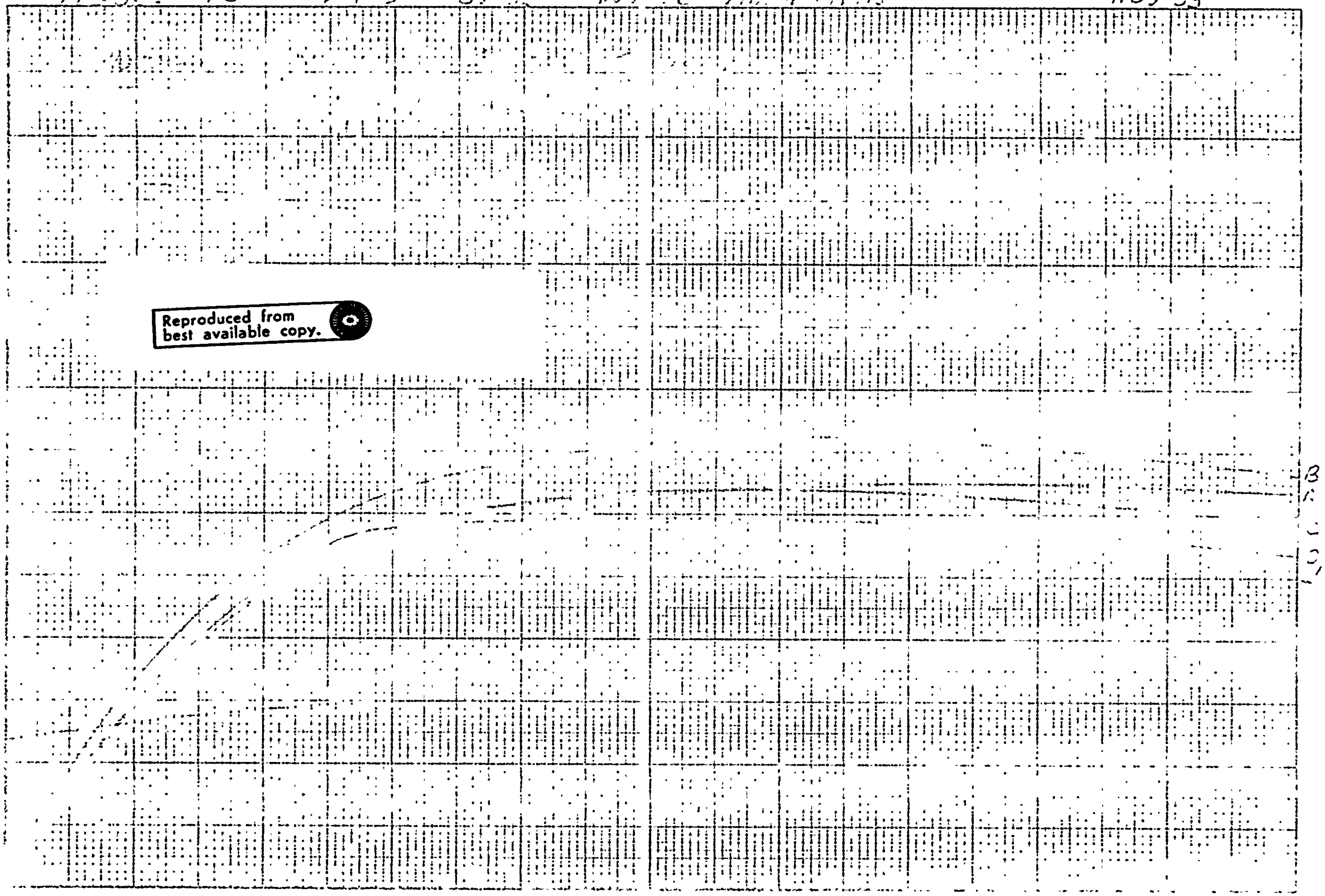
Panel 1109-54								
Specimen No.	2	4	6	8	10	12	14	16
Void Content (%)	3.3	2.4	4.8	10.4	1.4	0.37	0.21	1.19

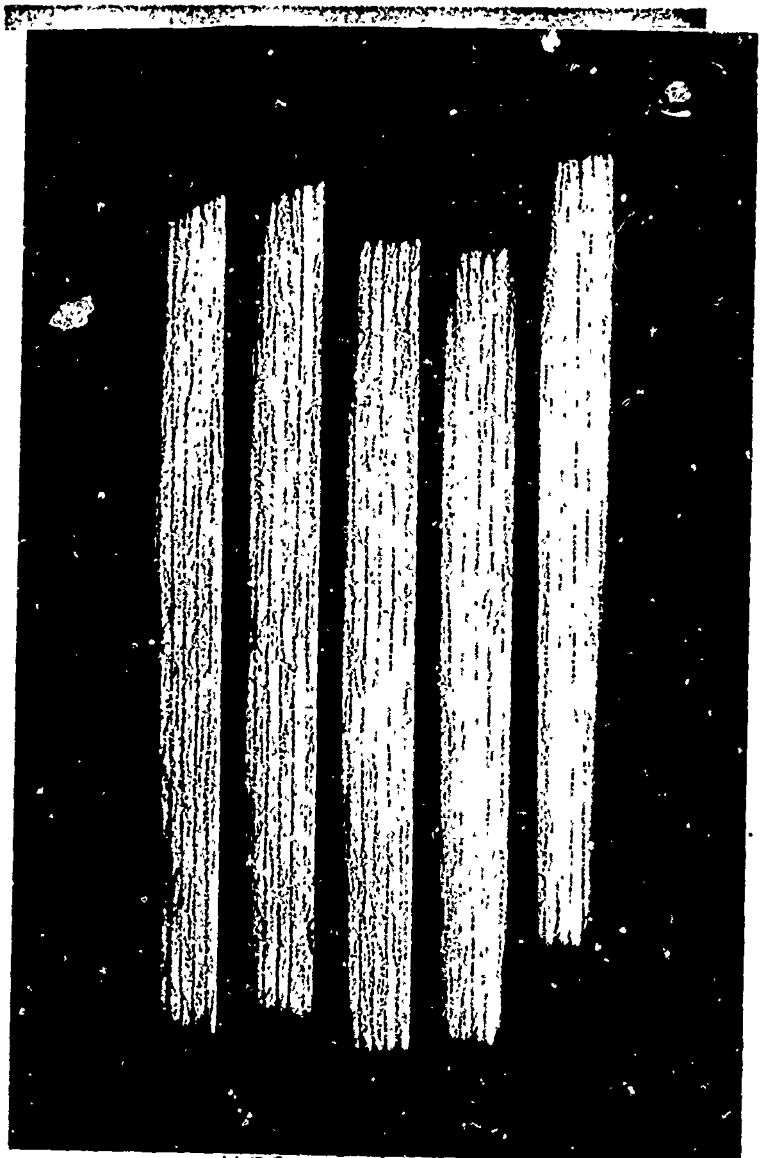
FIGURE 9b VOID CHARACTERIZATION SPECIMENS PANEL 1109-54

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-54 AC/ES 0° 12 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
2	.6	.9	3.3
4	.85	1.27	2.4
6	.8	1.2	4.8
8	1.8	2.7	10.4
10	.6	.9	1.4
12	.6	.9	.37
14	.45	.67	.21
16	.6	.9	1.19
		$\bar{X}$ 1.18	$\bar{X}$ 3.00

1109-53





1109-53

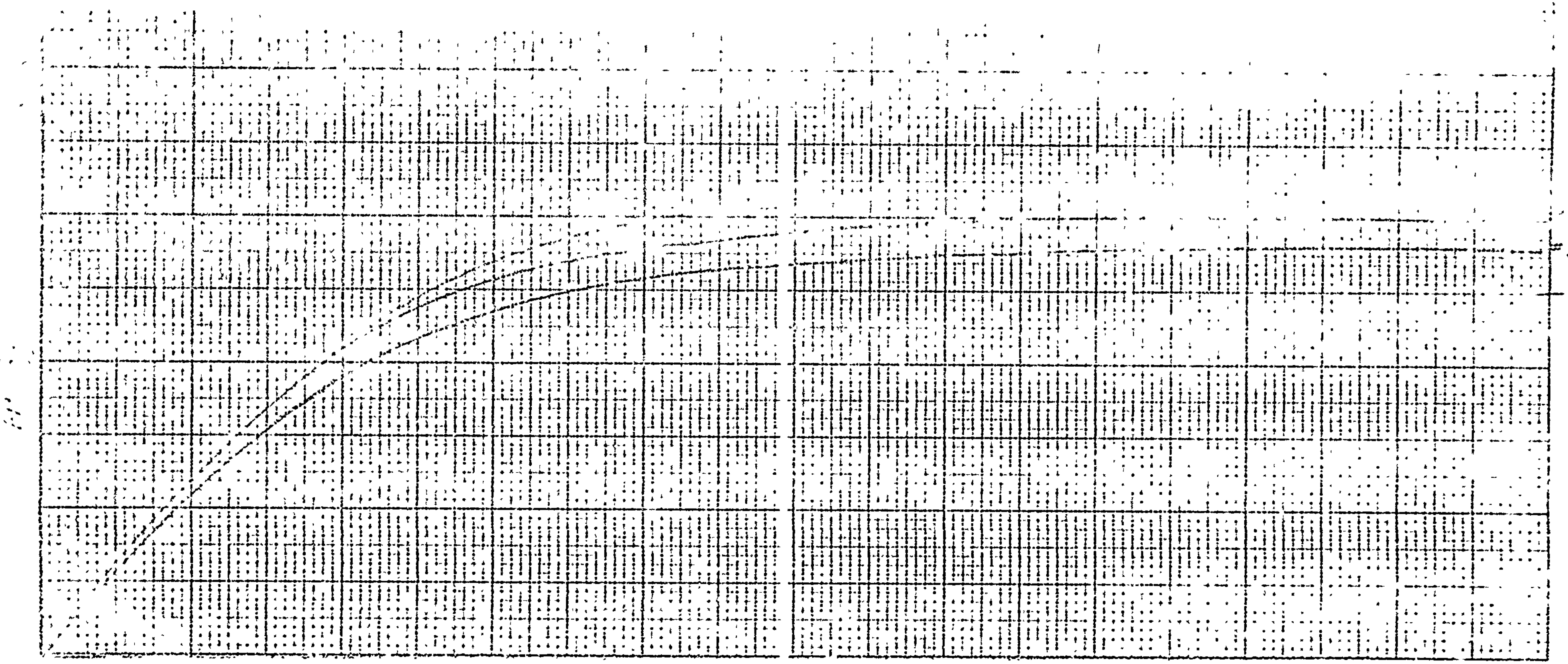
A B C D E

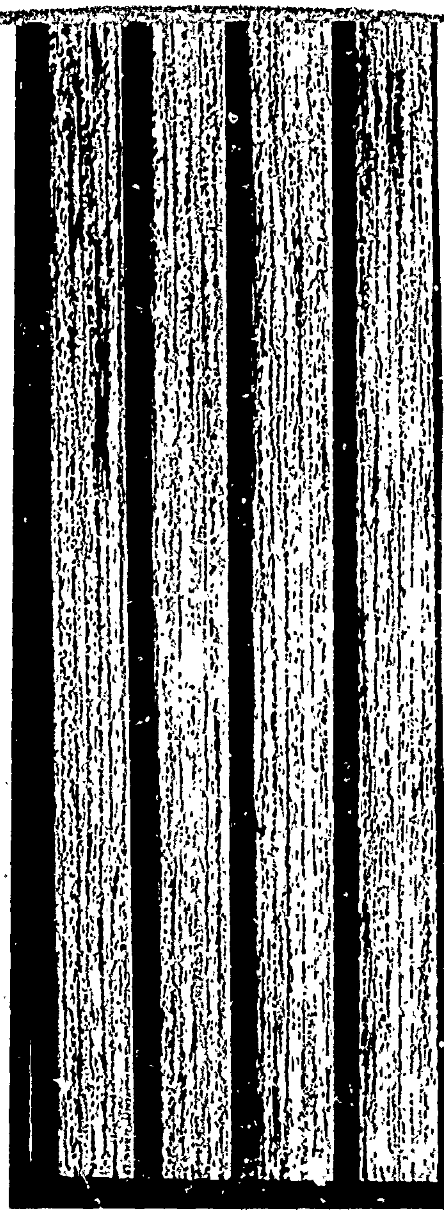
Panel 1109-53					
Specimen No.	A	B	C	D	E
Void Content (%)	.07	.16	.33	.28	.38

FIGURE 10b VOID CHARACTERIZATION SPECIMENS
PANEL 1109-53

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-53 AC/ES 0 6 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
A	.35	.52	.07
B	.4	.60	.16
C	.2	.30	.33
D	.1	.15	.28
E	.1	.15	.38
		$\bar{X}$ .34	$\bar{X}$ .24





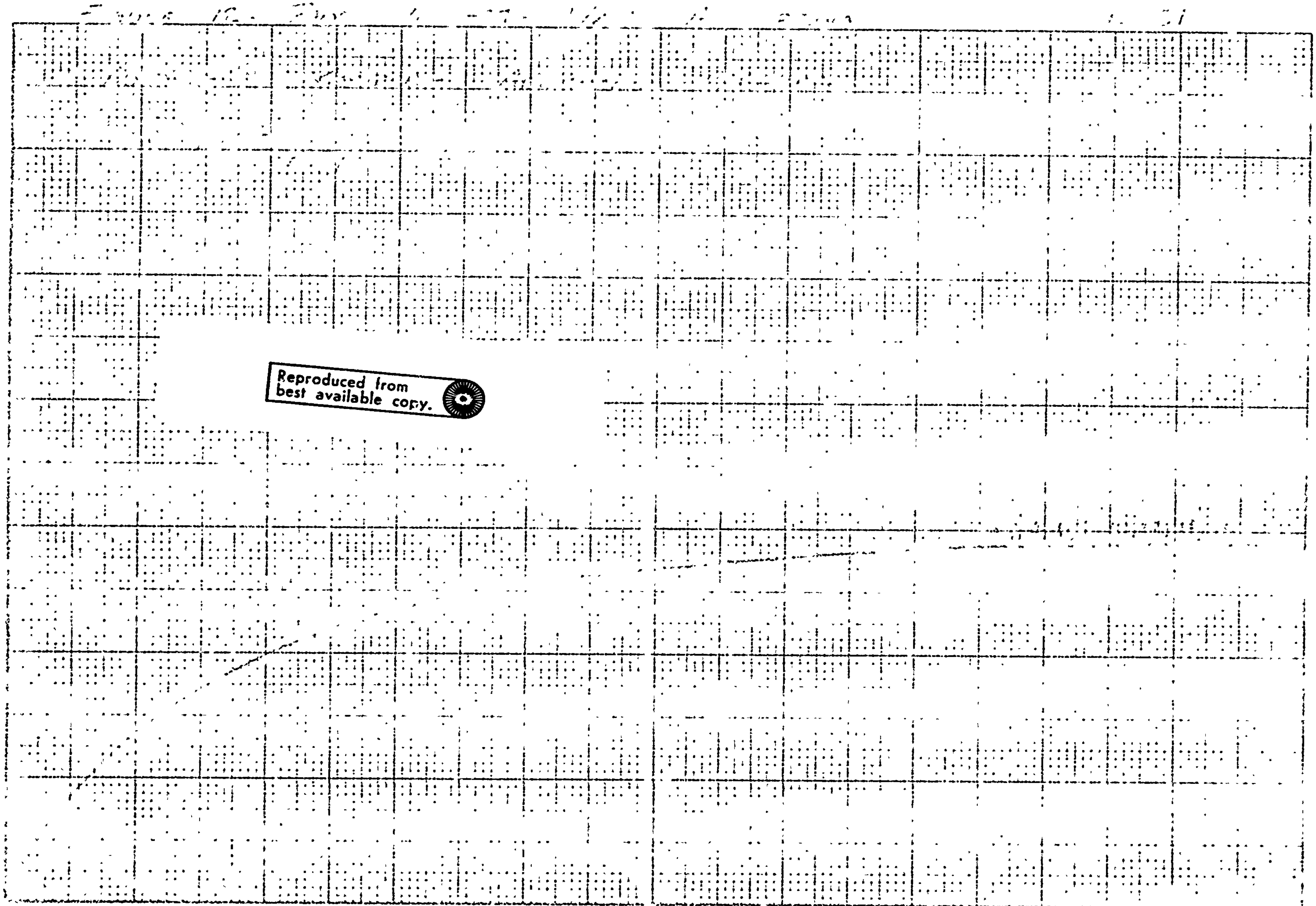
1109-58
4 3 2 1

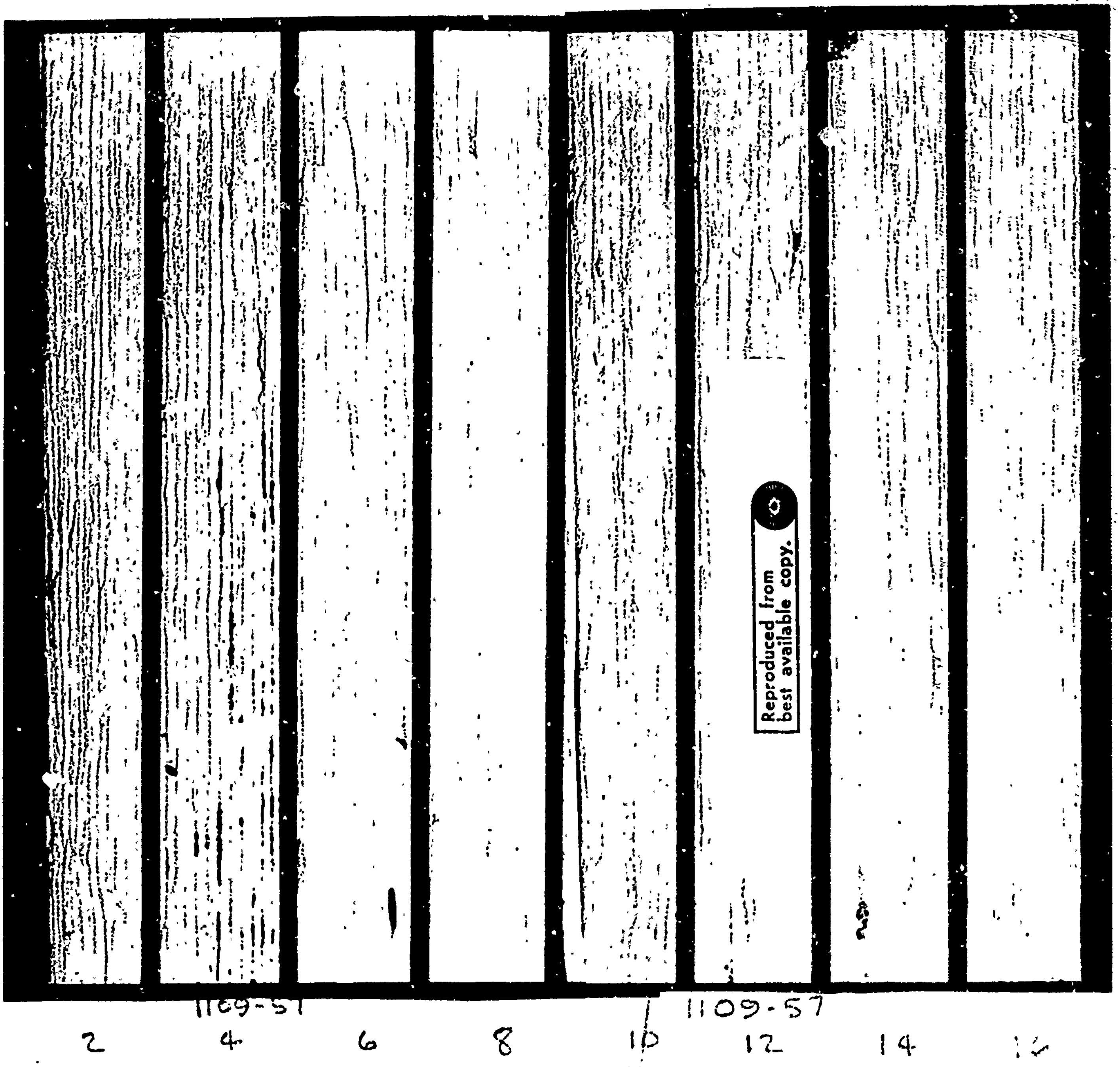
Panel 1109-58				
Specimen No.	1	2	3	4
Void Content (%)	.27	.18	.65	.42

FIGURE 11b VOID CHARACTERIZATION SPECIMEN
PANEL 1109-58

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-58 AC/AP 0/90 7 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
1	.3	.45	.27
2	.25	.37	.18
3	.15	.22	.65
4	.15	.22	.42
		$\bar{X}$ .37	$\bar{X}$ .31





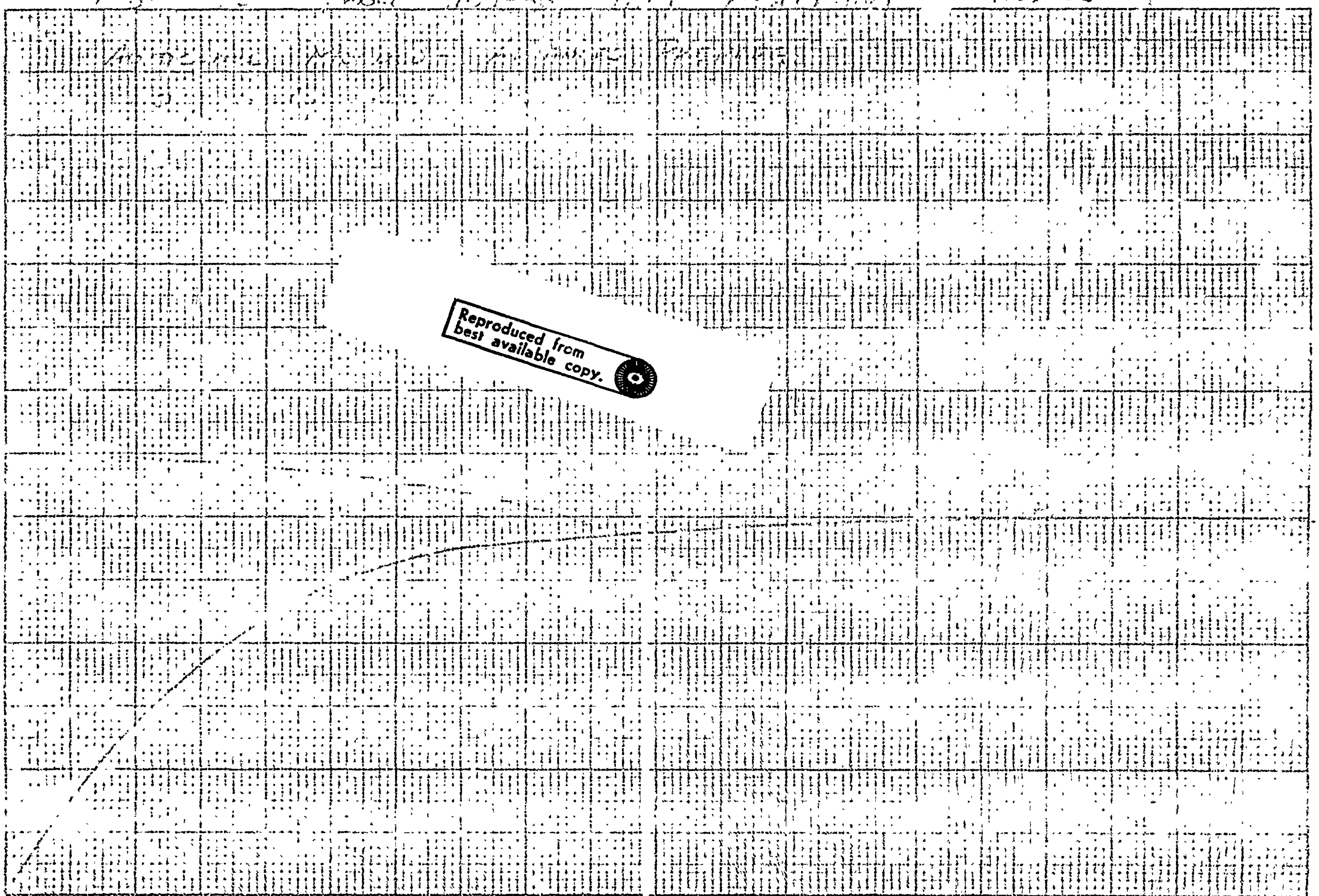
Panel 1109-57								
Specimen No.	2	4	6	8	10	12	14	16
Void Content (%)	1.09	2.24	.15	.14	.46	.55	.38	.65

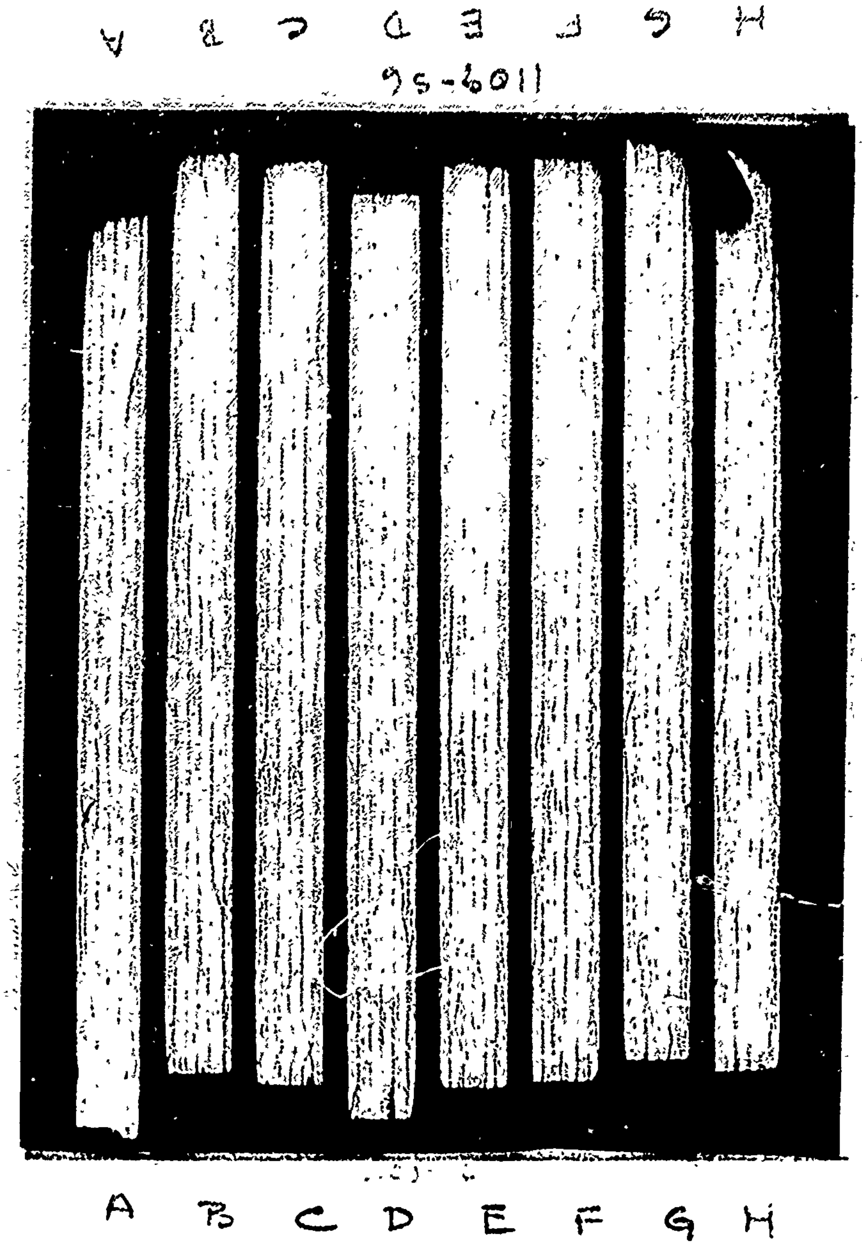
FIGURE 12b VOID CHARACTERIZATION SPECIMENS
PANEL 1109-57

SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-57 AC/AP 0° 12 PLY

	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
2	.2	.3	1.09
4	.2	.3	2.24
6	.2	.3	.15
8	.2	.3	.14
10	.2	.3	.46
12	.2	.3	.55
14	.2	.3	.38
16	.2	.3	.65
		$\bar{X}$ .3	$\bar{X}$ .707

1109-56





Panel 1109-56								
Specimen No.	A	B	C	D	E	F	G	H
Void Content (%)	.45	–	.23	.32	–	–	–	–

FIGURE 13b VOID CHARACTERIZATION SPECIMENS
PANEL 1109-56

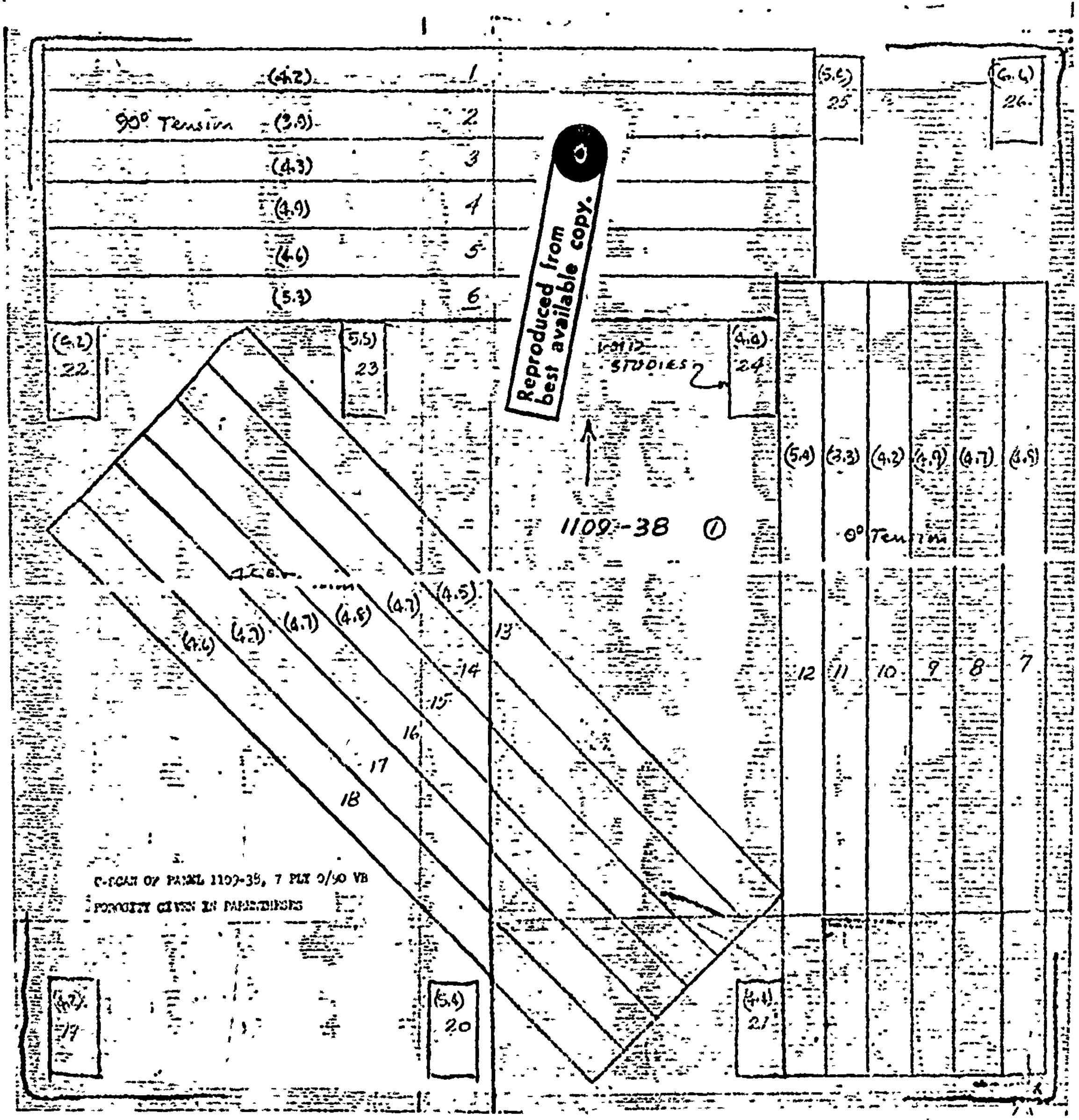
SUMMARY AND COMPARISON OF POROSITY DATA
PANEL 1109-56 AC/AP 0° 6 PLY

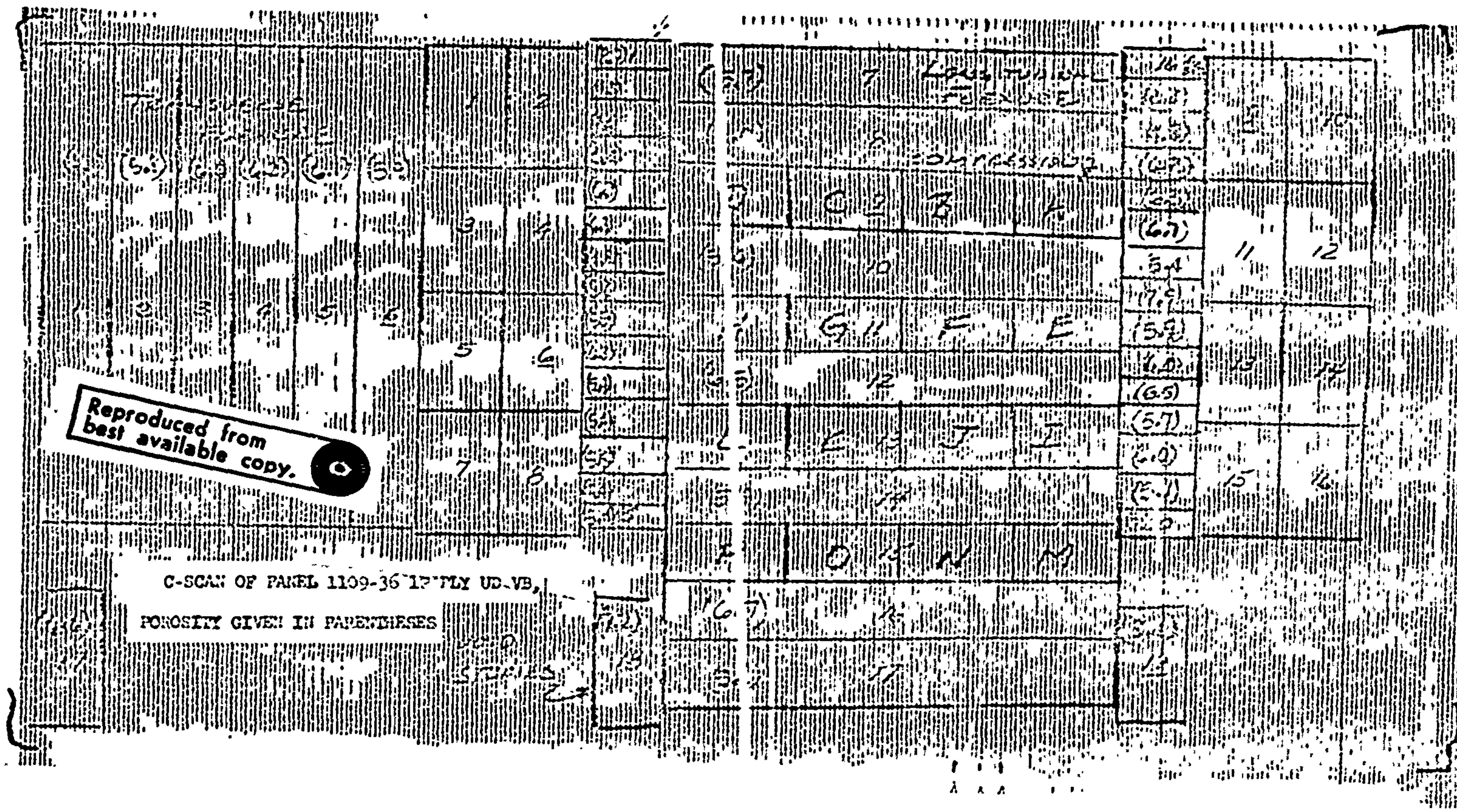
	Water Absorption		Point Count
Specimen Number	Excess Moisture (%)	Porosity (%)	Porosity (%)
A	.25	.37	.45
B	.25	.37	0
C	.25	.37	.23
D	.25	.37	.32
E	.25	.37	0
F	.25	.37	0
G	.25	.37	0
H	.25	.37	0
		$\bar{X}$ .37	$\bar{X}$ .125

APPENDIX D

C-SCANS OF TEST PANELS

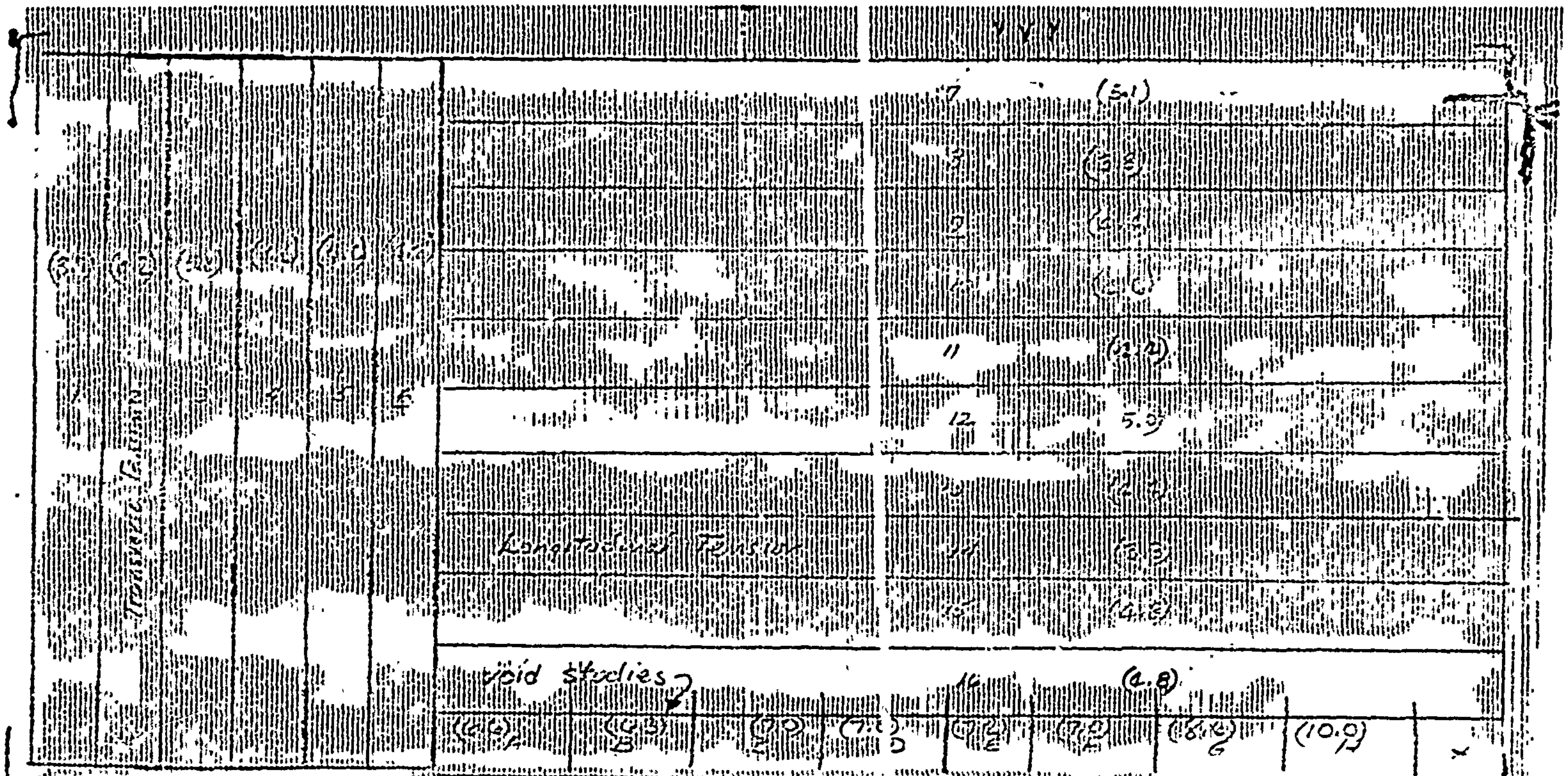
Sequence	Panel	Note
1	1109-38	Vacuum Bag
2	1109-36	Vacuum Bag
3	1109-37	Vacuum Bag
4	1109-41	Autoclave Molded
5	1109-39	Autoclave Molded
6	1109-40	Autoclave Molded
7	1109-55	Autoclave/Excess Solvent
8	1109-54	Autoclave/Excess Solvent
9	1109-53	Autoclave/Excess Solvent
10	1109-58	Autoclave/Advanced Prepreg
11	1109-57	Autoclave/Advanced Prepreg
12	1109-56	Autoclave/Advanced Prepreg


(4.2) 1
90° Tension (3.9) 2
(4.3) 3
(4.9) 4
(4.6) 5
(5.3) 6
(5.6) 25
(6.4) 26
(5.2) 22
(5.5) 23
(4.0) 24
VOID STUDIES
(5.4) (3.3) (4.2) (4.9) (4.7) (4.9)
1109-38 ①
0° Tension
12 11 10 9 8 7
(4.6) (4.2) (4.7) (4.8) (4.7) (4.5)
13 14 15 16 17 18
C-SCAN OF PANEL 1109-38, 7 PLY 0/90 VB
POROSITY GIVEN IN PARENTHESES
(4.2) 19
(5.4) 20
(4.4) 21



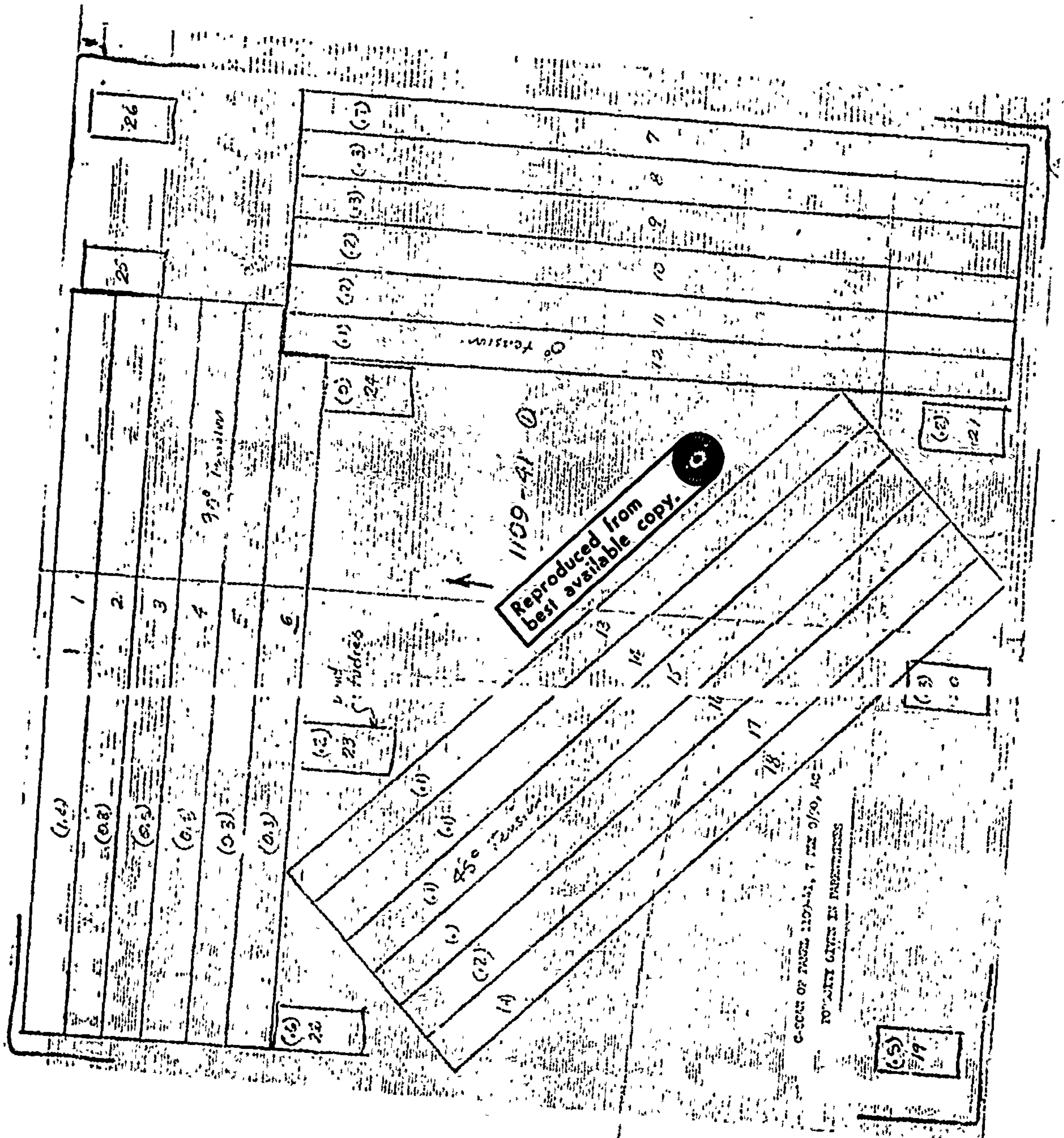
C-SCAN OF PANEL 1109-36 17 PLY UD-VB,

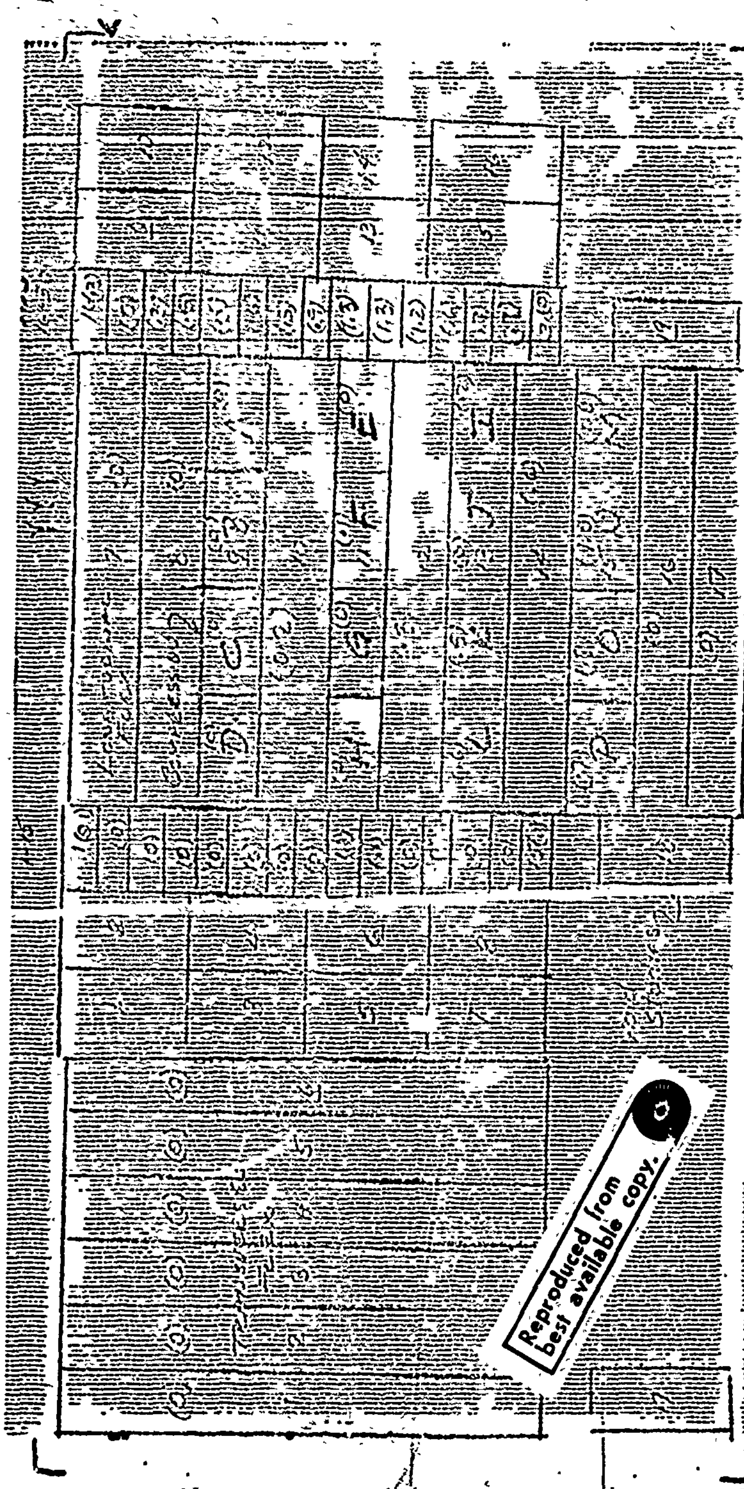
POROSITY GIVEN IN PARENTHESES



C-SCAN OF PANEL 1100-37, 6 PLY UD, AB

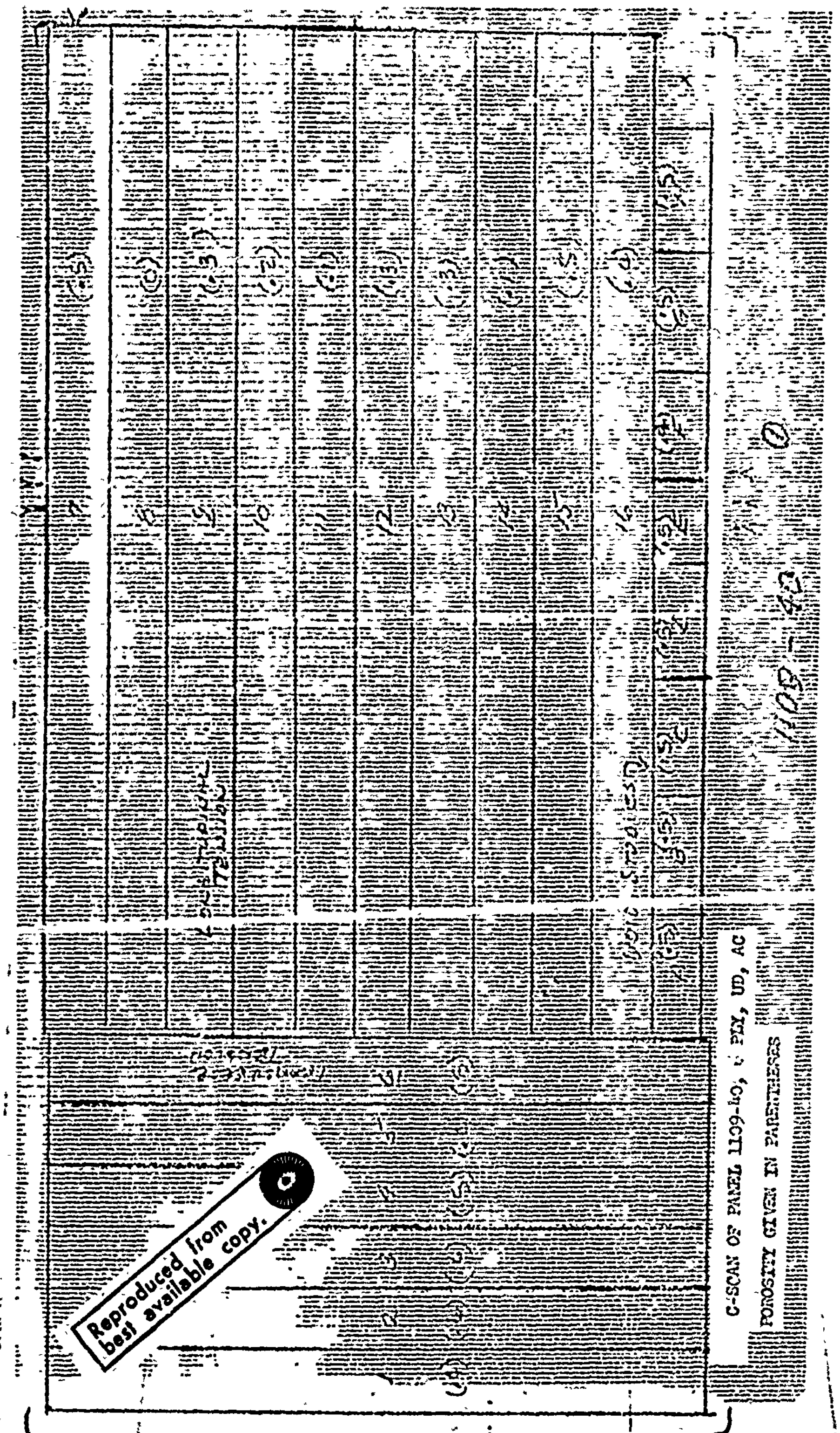
POROSITY GIVEN IN PARENTHESES


1109-41-0
0° Tension
45° Tension
90° Tension

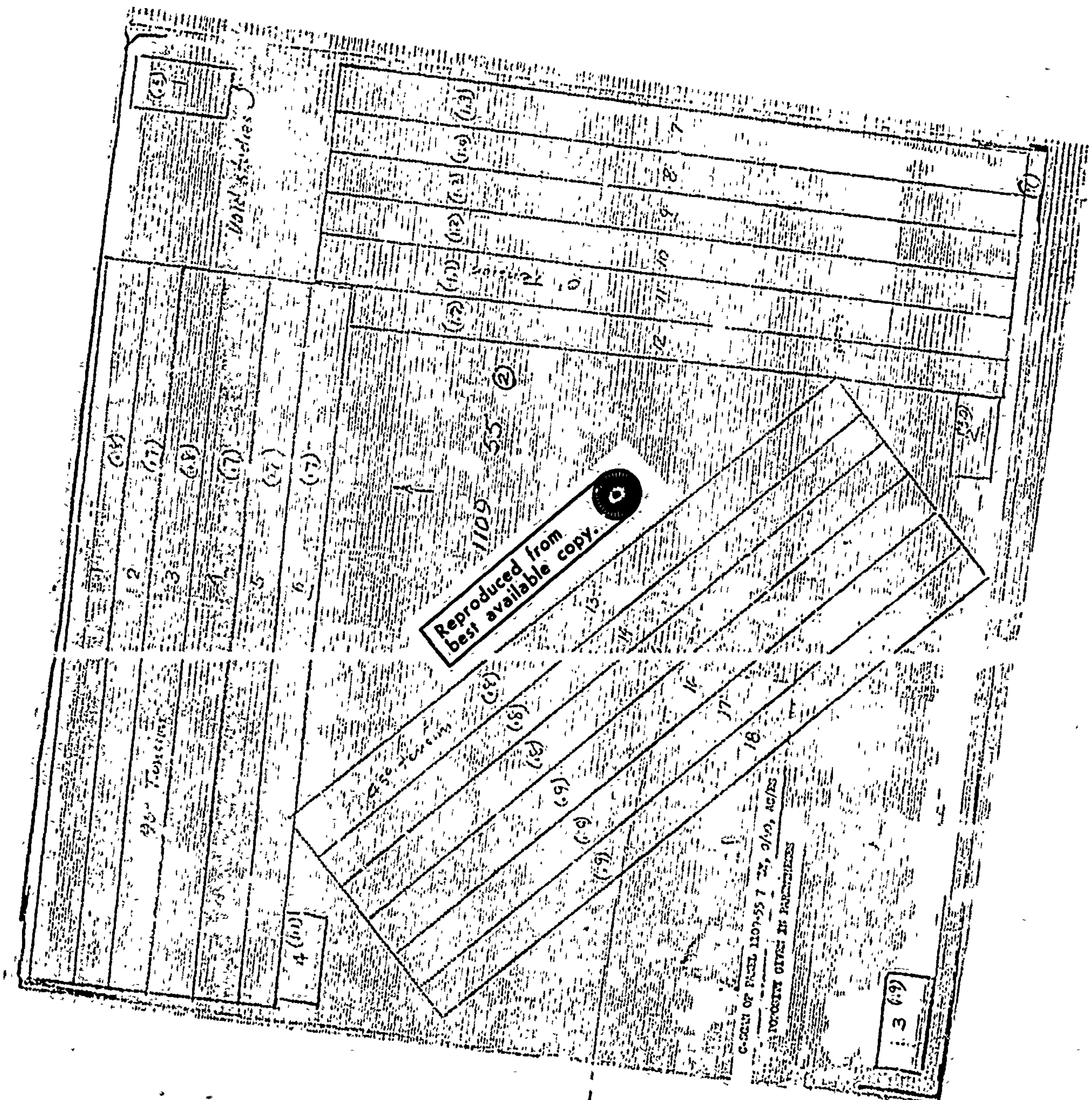


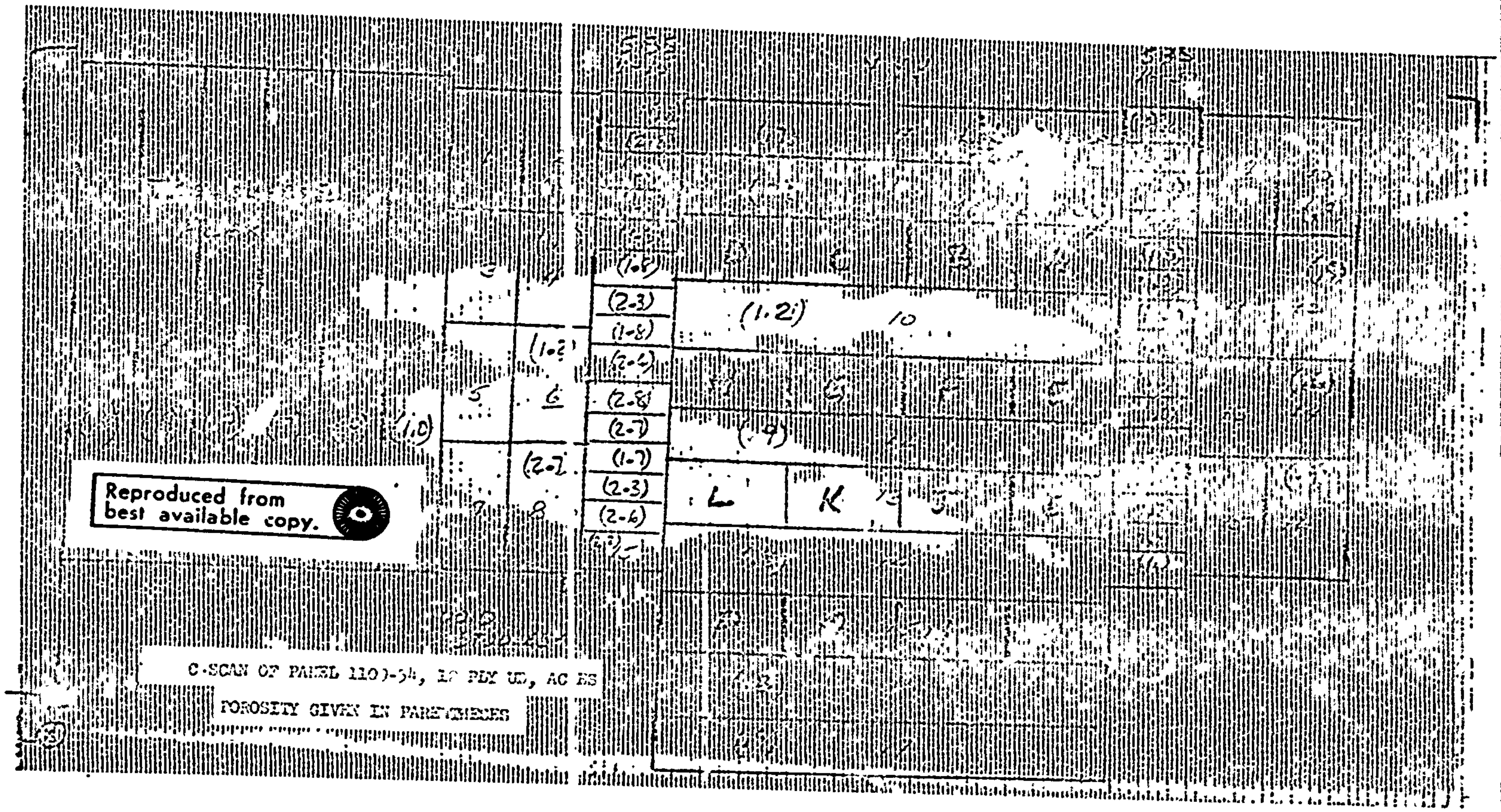
C-SCAN OF PANEL 1109-39, 12 PLY UD, AC

POROSITY GIVEN IN PARENTHESES



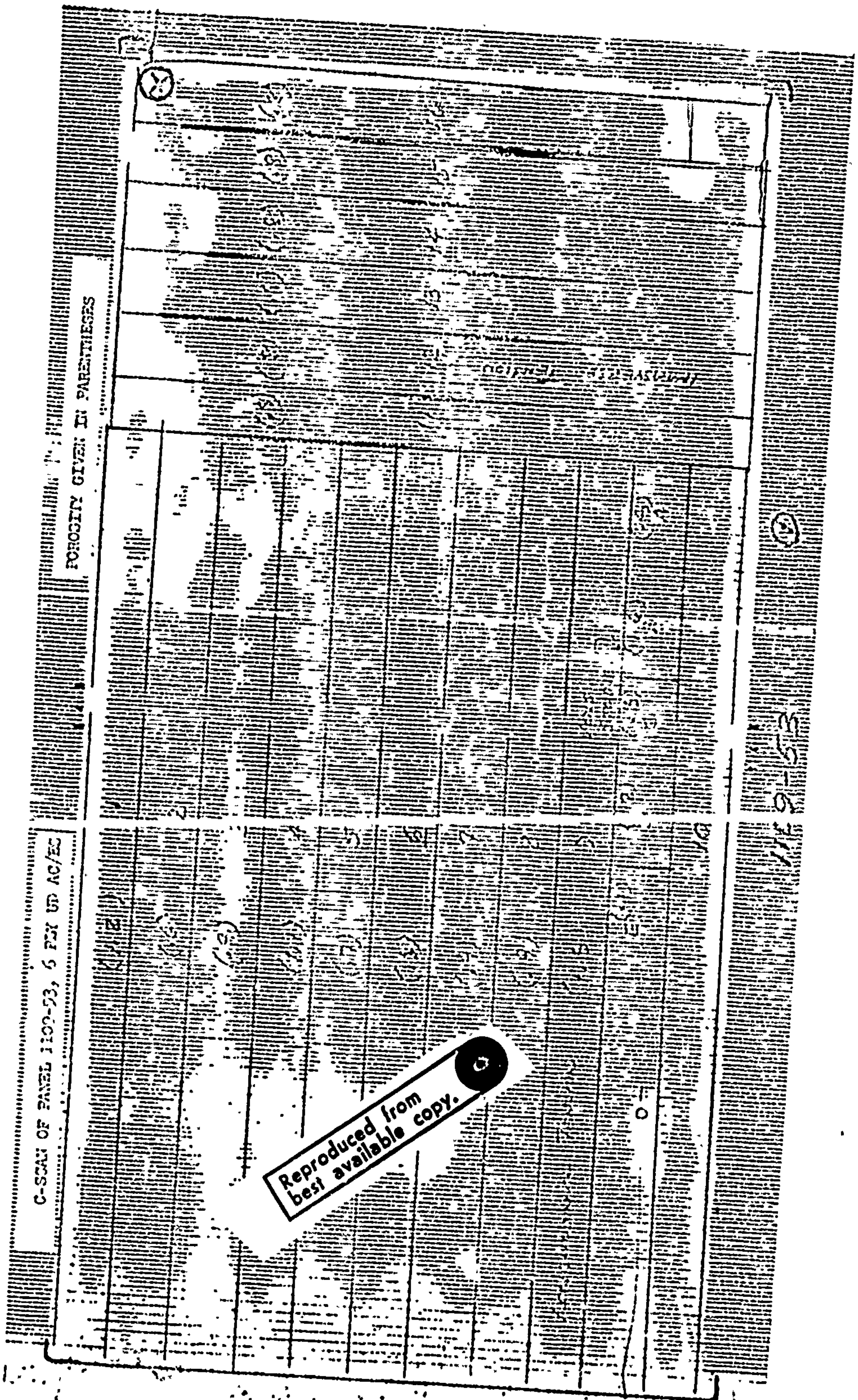
C-SCAN OF PANEL 1109-40, 8 PLY, UD, AC
POROSITY GIVEN IN PARENTHESES

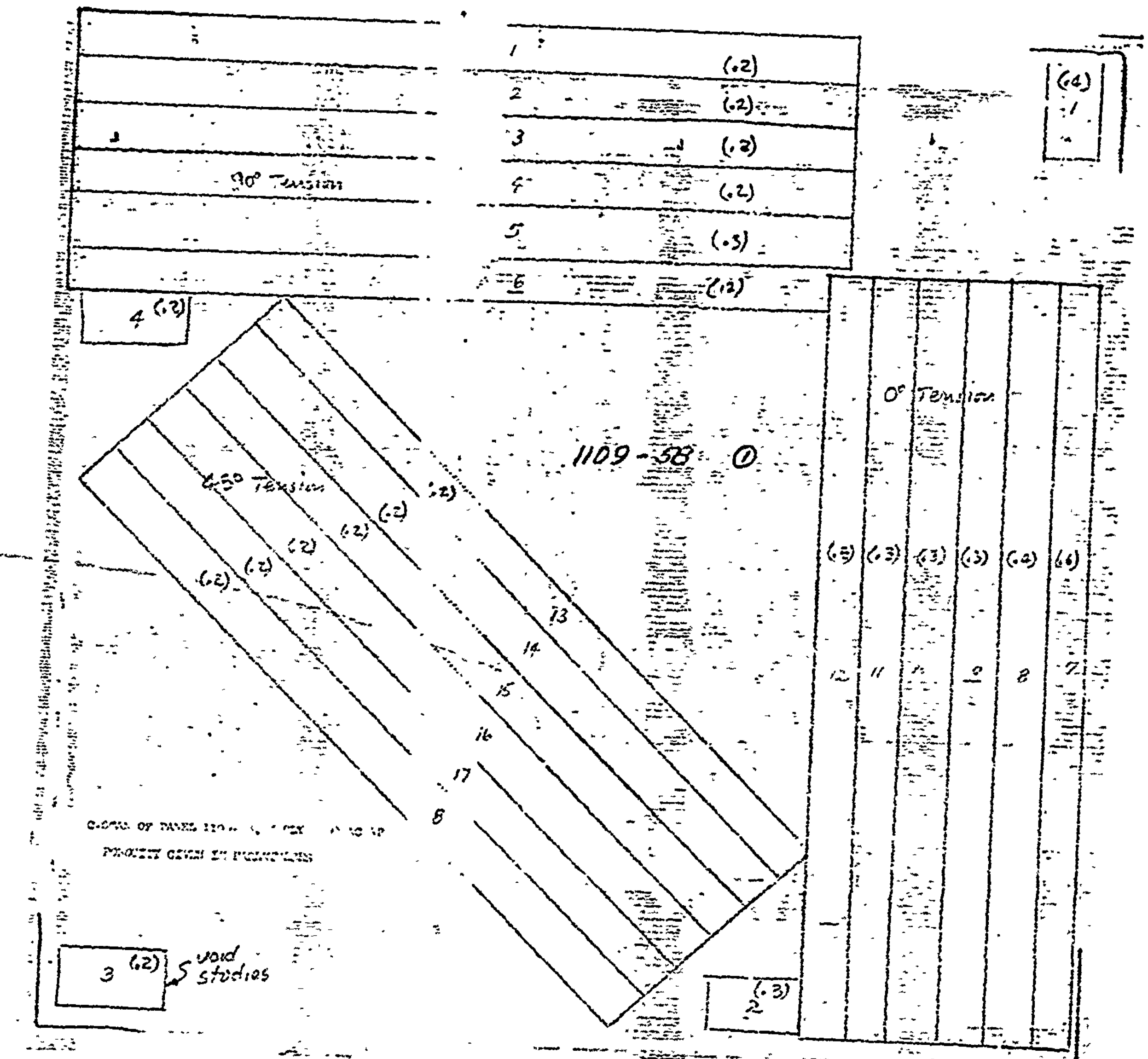


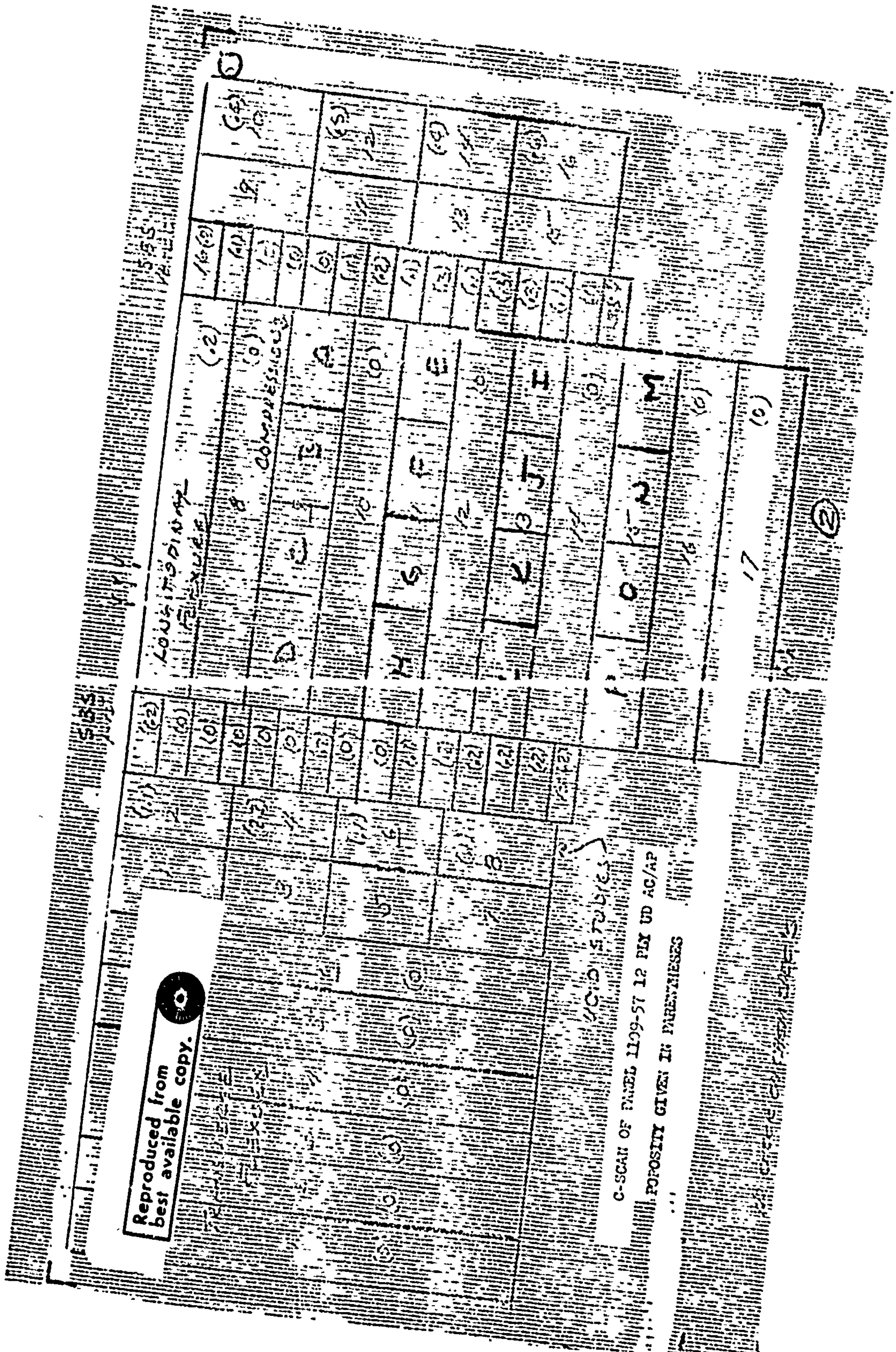


C-SCAN OF PANEL 110[illegible]-54, 1[illegible] PLY UD, AC ES

POROSITY GIVEN IN PARENTHESES

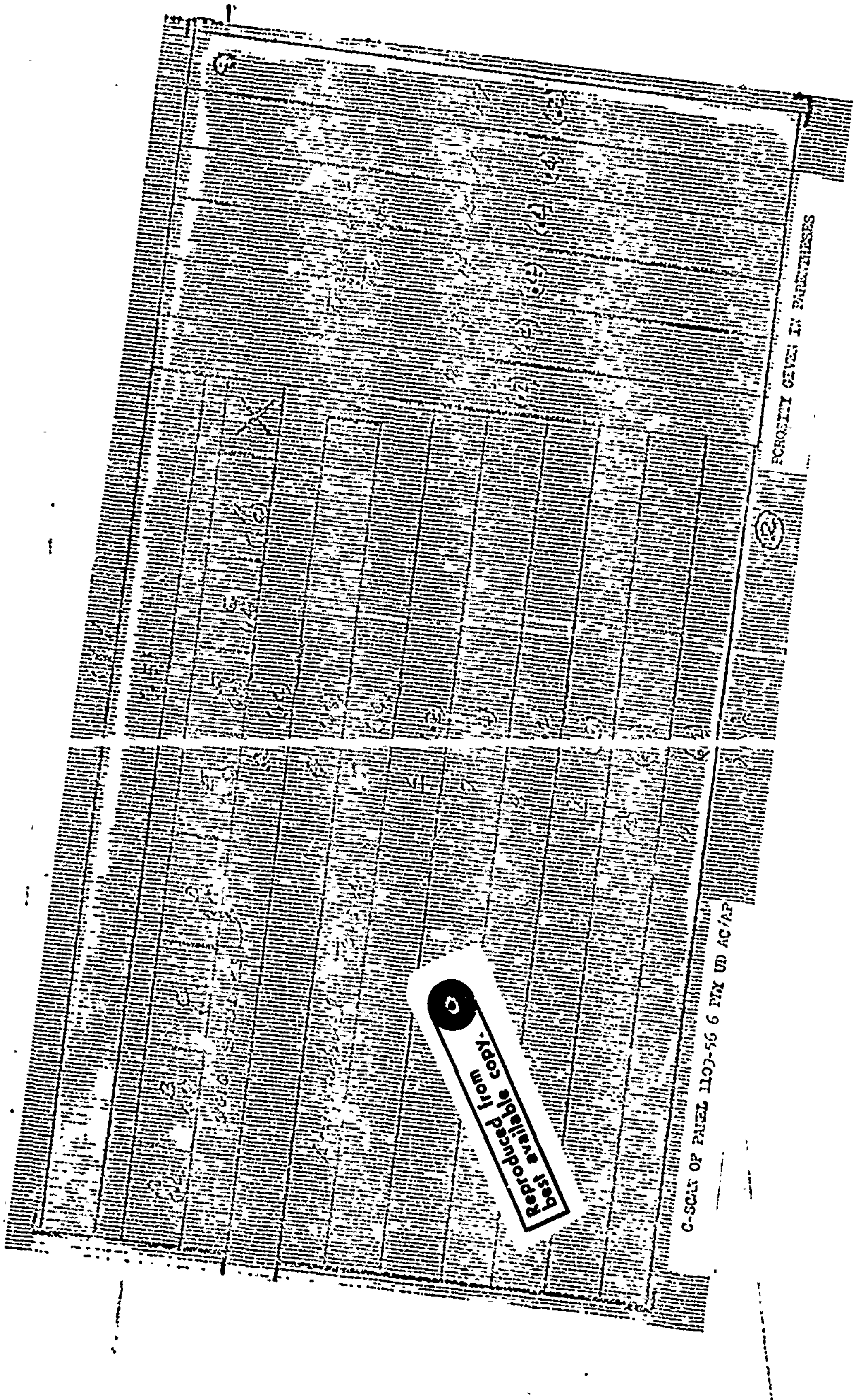

C-SCAN OF PANEL 1102-53, 6 PLY UD AC/EC
POROSITY GIVEN IN PARENTHESES
Reproduced from best available copy.


1109-58 ①
90° Tension
45° Tension
0° Tension
void studies



C-SCAN OF PANEL 1109-57 12 PLY UD AG/AP

POROSITY GIVEN IN PARENTHESES



POROSITY GIVEN IN PARENTHESES

C-SCAN OF PANEL 1109-56 6 PLY UD AC/AP

APPENDIX E

ULTRASONIC VELOCITY DATA FOR SPECIMENS FROM AUTOCLAVE AND VACUUM BAG MOLDED PANELS

DATA ON TRANSVERSE TENSION SPECIMENS
TEST TYPE G - REFER TO KEY AT END OF APPENDIX
6 PLY UD

Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
1109-37-1 (Vacuum Bag)	Good	8029	-11	low
2		8065	-47	
3		8016	+ 1	
4		8026	- 8	low
5		7995	+22	high
6	Good	7973	+44	high
		Ave. = 8017	C_v = .38%	
1109-40-1 (Autoclave)	Good	8301	-16	low
2		8226	+58	high
3		8287	- 2	high
4		8288	- 3	low
5		8316	- 3	
6	Good	8287	- 2	low
		Ave. = 8284	C_v = .31%	

DATA ON LONGITUDINAL TENSION SPECIMENS
TEST TYPE H - REFER TO KEY AT END OF APPENDIX
6 PLY UD

Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
Vacuum Bag				
1109-37-7	Poor	32688	-484	low
8	Good	32531	-357	
9	Poor	32212	- 38	
10	Poor	31456	+717	low
11	Good	32127	+ 46	high
12		31496	+677	high
13		32677	-503	low
14	Good	32832	-658	
15	Poor	32242	- 68	low
16	Good	31474	+699	high
		Ave. = 32173	C_v - 1.49%	

Autoclave				
1109-40-7	Poor	32764	-105	low
8	Good	32756	- 97	
9		32066	+592	
10		32586	+ 72	
11	Good	33119	-460	
12	Poor	32748	- 89	
13	Good	32869	-237	
14		33333	-674	
15		31801	+857	
16	Good	32517	+141	low
		Ave. = 32658	C_v = 1.37%	

DATA ON TRANSVERSE TENSION SPECIMENS
TEST TYPE C - REFER TO KEY AT END OF APPENDIX
7 PLY, $0/90/0/90/0/90/0^\circ$ PANELS

Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
Vacuum Bag				
1109-38-1	Poor	20038	+124	high
2		20313	-150	low
3		19699	+463	high
4		22804	-2641	high
5		19269	+893	low
6	Poor	18854	+1308	high
		Ave. = 20162	C_v = 6.92%	
Autoclave				
1109-41-1	Good	20804	-674	high
2	Distorted	- - -	- - -	high
3	Good	20804	-674	low
4		19737	+392	
5		20325	-195	
6	Good	18977	+1152	low
		Ave. = 20129	C_v = 3.46%	

DATA ON LONGITUDINAL TENSION SPECIMENS
TEST TYPE D - REFER TO KEY AT END OF APPENDIX
7 PLY 0/90

	Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
Vacuum Bag	1109-38-7	Poor	21744	+564	low
	8	Good	23115	-806	low
	9		22560	-251	high
	10		21902	+406	high
	11	Poor	22001	+307	high
	12	Good	22529	-220	low
			Ave. = 22308	C_v = 2.31%	

Autoclave	1109-41-7	Poor	22846	-109	high
	8	Good	23199	-462	
	9		23164	-427	high
	10	Good	22986	-249	low
	11	Poor	22470	+266	
	12	Poor	21754	+982	low
			Ave. = 22736	C_v = 2.41%	

Data on 45° Tension Specimen.
All Pulses Distorted - For Specimens 13 Through 18 For Both Panels.

DATA ON TRANSVERSE FLEXURE SPECIMENS
TEST TYPE A - REFER TO KEY AT END OF APPENDIX
12 PLY UD

Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
Vacuum Bag 1109-36-1	Good	8146	-102	low
2		8018	+ 25	low
3		8010	+ 33	high
4		8016	+ 27	
5		8043	0	
6	Good	8027	+ 16	high
		Ave. = 8043	C_v = .63%	
Autoclave 1109-39-1	Good	8168	- 23	low
2		8160	- 15	
3		8164	- 19	
4		8140	+ 5	
5		8110	+ 38	
6	Good	8128	+ 17	low
		Ave. = 8145	C_v = .27%	

DATA ON LONGITUDINAL FLEXURE SPECIMENS
TEST TYPE B - REFER TO KEY AT END OF APPENDIX
12 PLY UD

Vacuum Bag

Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
1109-36-7	Poor	31846	+175	low
8	Good	32340	-318	
9		31717	+304	
10		32107	- 85	
11		31665	+356	low
12		31907	+114	high
13		32030	- 8	high
14		32278	-256	low
15		31968	+ 35	low
16		32153	-131	high
17	Good	32207	-185	low
		Ave. = 32021	C_V = .6%	

Autoclave

1109-39-7	Good	33143	-442	low
8		33078	-377	
9		32570	+130	low
10		32633	+ 67	high
11		32008	+692	
12		32697	+ 3	high
13		32826	-125	low
14		32318	+382	
15		32697	+ 3	
16		32964	-263	
17	Good	32770	- 69	low
		Ave. = 32700	C_V = .91%	

DATA ON COMPRESSION TYPE SPECIMEN
TEST TYPE E, REFER TO KEY AT END OF APPENDIX
12 PLY UD

	Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
	1109-36-1	Good	9380	+ 6	low
	2		9398	- 11	low
	3		9326	+ 60	high
	4		9276	+110	
	5		9356	+ 30	
	6		9347	+ 39	high
	7		9472	- 85	low
V. uum Bag	8		9486	- 99	
	9		9298	+ 88	
	10		9380	+ 6	low
	11		9380	+ 6	high
	12		9389	- 3	high
	13		9380	+ 6	low
	14		9380	+ 6	
	15		9465	- 78	
	16	Good	9477	- 90	low
			Ave. = 9386	C_V = .61%	
	1109-39-1	Good	9998	-213	low
	2		10034	-249	
	3		9857	- 72	
Autoclave	4		9940	-155	
	5		9831	- 46	
	6		9844	- 59	
	7		9857	- 72	
	8		9893	-108	low
	9		9937	-152	low
	10		9974	-189	
	11		9765	+ 19	
Autoclave	12		9661	+123	low
	13		9432	+352	high
	14		9377	+407	
	15		9529	+255	
	16	Good	9626	+158	high
			Ave. = 9784	C_V = 1.95%	

DATA ON SHORT BEAM SHEAR SPECIMENS
TEST TYPE F - REFER TO KEY AT END OF APPENDIX
12 PLY UD

	Specimen No.	Acoustic Pulse Transmission	Velocity Feet/Second	Variation From Ave. Velocity	Attenuation From C-Scan
	1109-36-1	Good	39453	+4886	low
	2		45089	- 749	
	3		43534	+ 805	
	4		45089	- 749	
	5		45089	- 749	
	6		45089	- 749	
	7		45909	-1569	
	8		45089	- 749	
	9		44298	+ 41	low
	10		44298	+ 41	high
	11		43534	+ 805	high
	12		45909	-1569	low
	13		45089	- 749	
	14		46759	-2419	
Bag	15		45909	-1569	
			Ave = 44675		
			Cv = 3.78%		
	16		42083	+2256	
	17		45089	- 749	
Vacuum	18		45089	- 749	
	19		42726	+1613	low
	20		[illegible]298	+ 41	high
	21		43534	+ 805	high
	22		42797	+1542	low
	23		44298	+ 41	
	24		43534	+ 805	
	25		43534	+ 805	low
	26		43534	+ 805	high
	27		44298	+ 41	low
	28		44298	+ 41	
	29		45909	-1569	
	30	Good	45015	- 675	low
			Ave = 44002		
			Cv = 2.35%		

Overall Ave = 44339
Cv = 2.99%

SHORT BEAM SHEAR (Continued)

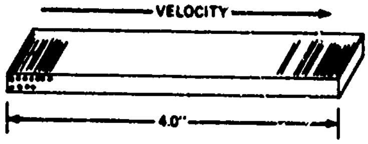
1109-39-1	Good	44006	+2081	low
2		47327	-1239	
3		46373	- 285	
4		46373	- 285	
5		45530	+ 557	
6		44717	+1370	
7		46373	- 285	
8		47248	-1160	
9		46373	- 285	
10		47248	-1160	
11		46373	- 285	
12		46373	- 285	
13		46373	- 285	
14		48237	-2149	
15		47237	-1239	
Autoclave		Ave = 46410 Cv = 2.2%		
16		44006	+2081	
17		47327	-1239	
18		47248	-1160	
19		45530	+ 557	
20		45455	+ 632	
21		45455	+ 632	
22		47170	-1082	
23		46296	- 208	
24		43860	+2227	high
25		44643	+1444	
26		47170	-1082	
27		45530	+ 557	
28		45530	+ 557	
29		46373	- 285	
30	Good	44792	+1295	
		Ave = 45759 Cv = 2.5%		

Overall Ave = 46087
Cv = 2.33%

SPECIMEN TYPES

TYPE "A"

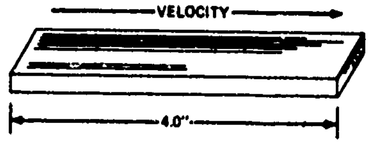
TRANSVERSE FLEXURE



SIZE: 4.0 x 0.500" x 12 PLYS
0° LAMINATE

TYPE "B"

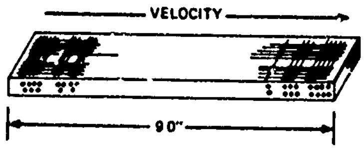
LONGITUDINAL FLEXURE



SIZE: 4.0 x 0.500" x 12 PLYS
0° LAMINATE

TYPE "C"

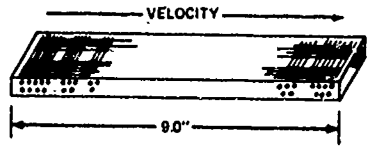
TRANSVERSE TENSION



SIZE: 9.0 x 0.500" x 7 PLYS
OUTER PLY 90°
0/90° LAMINATE

TYPE "D"

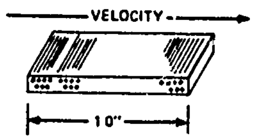
LONGITUDINAL TENSION



SIZE: 9.0 x 0.500" x 7 PLYS
OUTER PLY 0°
0/90° LAMINATE

TYPE "E"

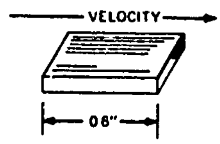
COMPRESSION



SIZE: 1.0 x 0.500" x 12 PLYS
0° LAMINATE

TYPE "F"

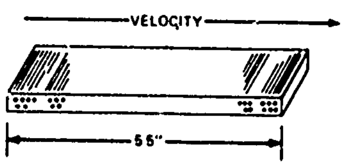
SHORT BEAM SHEAR



SIZE: 0.6 x 0.250" x 12 PLYS
0° LAMINATE

TYPE "G"

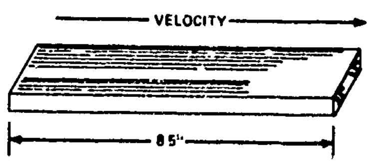
TRANSVERSE TENSION



SIZE: 5.5 x 0.500" x 6 PLYS
0° LAMINATE

TYPE "H"

LONGITUDINAL TENSION



SIZE: 8.5 x 0.500" x 6 PLYS
0° LAMINATE

APPENDIX F

MECHANICAL PROPERTIES AS A FUNCTION OF POROSITY

1. Tension on UD Panels
2. Compression on UD Panels
3. Flexure on UD Panels
4. Shear on UD Panels
5. Tension on Cross Ply Panels

1. TENSION IN UD PANELS

1109-37 VB
1109-40 AC
1109-53 AC/ES
1109-56 AC/AP

MECHANICAL PROPERTIES
1109-37 0^{o} 6 PLY VACUUM BAG

Longitudinal Tension (LT)					
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)	Velocity fps
LT 7	117	17.6	0.65	5.10	32688
8	183	19.7	0.87	3.82	32531
9	176	19.4	0.84	4.42	32212
10	162	17.4	0.87	4.68	31456
11	142	18.4	0.74	4.44	32127
12	130	17.1	0.75	5.02	31496
13	160	18.5	0.81	4.48	32677
14	189	19.6	0.91	3.31	32832
15	155	18.3	0.82	4.81	32242
16	135	17.5	0.74	4.83	31474
Average	155	18.35	0.80	4.49	32173
Cv	15.3	5.22	9.9	12.3	1.5%

Transverse Tension (TT)					
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)	Velocity fps
TT 1	4140	1.01	0.41	3.71	8029
2	4470	1.05	0.43	4.24	8065
3	4880	1.17	0.41	5.83	8016
4	3670	1.04	0.36	4.66	8026
5	3960	1.03	0.38	4.61	7995
6	4780	1.05	0.46	4.22	7973
Average	4320	1.06	0.41	4.54	8017
Cv	11.0	5.35	8.6	15.7	.38%

MECHAHNICAL PROPERTIES
1109-40 0° 6 PLY AUTOCLAVE

Longitudinal Tension (LT)					
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)	Velocity fps
LT 7	136	19.1	0.71	.51	32764
8	168	21.6	0.76	.00	32756
9	156	21.7	0.71	.36	32066
10	159	21.7	0.74	.22	32586
11	173	22.8	0.79	.07	33119
12	143	20.6	0.70	.36	32748
13	132	20.5	0.64	.27	32869
14	177	24.4	0.71	.12	33333
15	152	19.6	0.76	.52	31801
16	170	21.7	0.78	.37	32517
Average	157	21.4	0.73	.28	32658
Cv	10.0	7.18	6.16	- -	1.37

Transverse Tension (TT)					
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)	Velocity fps
TT 1	4820	1.15	0.43	.37	8301
2	4410	1.14	0.38	.65	8226
3	4400	1.27	0.35	.57	8287
4	3950	1.15	0.36	.52	8288
5	4680	1.18	0.42	.41	8316
6	4460	1.16	0.40	.51	8287
Average	4450	1.18	0.39	.51	8284
Cv	6.1	4.1	0.20	- -	.31

MECHANICAL PROPERTIES
1109-53 0° 6 PLY AUTOCLAVE - EXCESS SOLVENT

Longitudinal Tension (LT)				
Specimen Number	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)
LT 1	157	20.0	0.79	1.25
2	147	20.8	0.71	.66
3	138	20.8	0.67	.96
4	138	19.2	0.73	1.14
5	169	19.8	0.80	.71
6	176	21.6	0.93	.83
7	116	19.1	0.63	.98
8	153	20.2	0.78	.92
9	186	20.2	0.90	1.55
10	152	19.0	0.78	1.38
Average	153	20.07	0.77	1.03
Cv	13.3	4.19	12.1	- -

Transverse Tension (TT)				
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Strain to Failure (%)	Porosity (%)
TT 11	6000	1.24	0.48	.81
12	6500	1.25	0.56	.84
13	6380	1.35	0.48	.82
14	6340	1.24	0.52	.84
15	6410	1.24	0.56	.84
16	5200	1.20	0.45	.82
Average	6140	1.25	0.51	.83
Cv	7.9	4.04		- -

MECHANICAL PROPERTIES
1109-56 0° 6 PLY AUTOCLAVE - ADVANCED PREPREG

Longitudinal Tension (LT)				
Specimen Number	Strength (KSI)	Modulus (x10^{-6} psi)	Strain to Failure (%)	Porosity (%)
LT 1	161	19.1	0.82	0.52
2*	- -	- -	- -	- -
3	177	19.0	.84	.47
4	191	19.4	.93	.52
5	201	19.7	.99	.47
6	187	20.4	.95	.24
7	145	20.3	.69	.36
8	186	18.7	1.03	.42
9	186	21.4	.86	.34
10	156	21.6	.71	.25
11	180	20.6	.87	.38
Average	177	20.1	.87	.39
Cv	9.9	4.7	12.8	- -

Transverse Tension (TT)				
Specimen Number	Strength (psi)	Modulus (x10^{-6} psi)	Strain to Failure (%)	Porosity (%)
TT 12	4360	1.23	0.37	.24
13	4470	1.25	0.37	.41
14	3910	1.26	0.33	.36
15	4910	1.20	0.41	.38
16	4210	1.16	0.36	.36
17	3880	1.31	0.30	.24
Average	4290	1.24	0.34	.33
Cv	8.9	4.16	11.1	- -

*Missing, cut up for void characterization studies.

2. COMPRESSION IN UD PANELS

1109-36 VB
1109-39 AC
1109-54 AC/ES
1109-57 AC/AP

MECHANICAL PROPERTIES
1109-36 0° 12 PLY VACUUM BAG

	Compression	
Specimen	Strength (KSI)	Porosity (%)
A	72.0	5.55
B	123.0	5.32
C	140.0	6.32
D	79.7	6.77
E	71.5	6.75
F	124.0	6.43
G	136.0	5.75
H	71.9	5.65
I	108.0	6.46
J	144.0	5.86
K	129.0	6.15
L	113.0	4.26
M	117.0	4.21
N	129.0	4.32
O	131.0	5.40
P	100.0	6.06
Average	111.0	5.69
Cv	22%	14.9

MECHANICAL PROPERTIES
1109-39 0° 12 PLY AUTOCLAVE

	Compression	
Specimen	Strength (KSI)	Porosity (%)
A	159	0
B	166	0
C	171	0
D	147	0
E	141	.07
F	161	.09
G	- -	0
H	143	0
I	155	.22
J	167	.07
K	187	.54
L	145	.63
M	154	1.06
N	172	1.05
O	154	.81
P	137	.71
Average	157	0.32
Cv	9	- -

MECHANICAL PROPERTIES (VIRGIN)
1109-54 0° 12 PLY - EXCESS SOLVENT

	Compression	
Specimen	Strength (KSI)	Porosity (%)
A	135	Not Determined
B	151	
C	152	
D	102	
E	140	
F	157	
G	123	
H	105	
I	142	
J	139	
K	136	
L	109	
M	139	
N	155	
O	157	
P	97.4	
Average	133	
Cv	15	

MECHANICAL PROPERTIES (VIRGIN)
1109-57 0° 12 PLY - ADVANCED PREPREG

	Compression	
Specimen	Strength (KSI)	Porosity (%)
A	130	Not Determined
B	122	
C	120	
D	108	
E	123	
F	147	
G	171	
H	110	
I	109	
J	149	
K	150	
L	125	
M	112	
N	130	
O	127	
P	95.9	
Average	126	
Cv	15	

3. FLEXURE IN UD PANELS

1109-36 VB
1109-39 AC
1109-54 AC/ES
1109-57 AC/AP

MECHANICAL PROPERTIES
1109-36 0° 12 PLY VACUUM BAG

Transverse Flexure (TF)				
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)	Velocity fps
TF 1	7480	1.16	4.70	8146
2	7240	1.12	5.86	8018
3	8280	1.17	6.05	8010
4	6770	1.16	6.20	8016
5	6910	1.17	6.16	8043
6	7550	1.20	5.92	8027
Average	7370	1.16	5.81	8043
Cv	7.33	2.22	9.67	0.63

Longitudinal Flexure (LF)				
Specimen Number*	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)	Velocity fps
LF 7	177	14.9	5.76	31846
8	176	17.4	5.00	32340
10	180	17.1	5.56	32107
12	165	16.9	6.55	31907
14	166	17.6	5.95	32278
16	165	17.2	6.67	32153
17	165	17.9	5.20	32207
Average	171	17.0	5.81	32119
Cv	3.94	5.78	10.88	0.57

*Missing specimens were cut up into compression specimens.

MECHANICAL PROPERTIES
1109-39 0° 12 PLY AUTOCLAVE

Transverse Flexure (TF)				
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)	Velocity fps
TF 1	902	1.32	0	8168
2	107	1.38	0	8160
3	103	1.40	0	8164
4	106	1.53	0	8140
5	956	1.51	0	8110
6	839	1.47	0	8128
Average	9.76	1.43	0	8145
Cv	9.6	5.7	-	0.27

Longitudinal Flexure (LF)				
Specimen Number*	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)	Velocity fps
LF 7	220	19.6	0	33143
8	262	20.3	0	33078
10	215	19.8	.21	32633
12	237	20.6	.37	32697
14	230	19.9	.46	32318
16	229	20.3	0	32964
17	262	20.8	0	32770
Average	236	20.2	.14	32800
Cv	8.0	2.16	- -	0.87

*Missing specimens were cut up into compression specimens.

MECHANICAL PROPERTIES
1109-54 0° 12 PLY AUTOCLAVE - EXCESS SOLVENT

Transverse Flexure (TF)			
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)
TF 1	122	1.43	.87
2	130	1.47	.94
3	112	1.44	.96
4	117	1.59	.72
5	114	1.52	.91
6	111	1.51	.97
Average	118	1.49	.90
Cv	6.13	4.0	10.4

Longitudinal Flexure (LF)			
Specimen Number*	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)
LF 7	203	16.8	.72
8	222	19.2	.71
10	195	18.5	1.17
12	214	19.7	.89
14	221	19.4	.80
16	208	19.6	.84
17	221	19.7	.92
Average	212	19.0	.86
Cv	4.9	5.5	18.2

*Missing specimens were cut up into compression specimens.

MECHANICAL PROPERTIES
1109-57 0^{o} 12 PLY AUTOCLAVE - ADVANCED PREPREG

Transverse Flexure (TF)			
Specimen Number	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)
TF 1	9190	1.40	0.06
2	9810	1.38	0.01
3	8960	1.39	0
4	10,000	1.50	0
5	10,400	1.49	0
6	8540	1.43	0
Average	9500	1.43	.01
Cv	7.55	3.63	- -

Longitudinal Flexure (LF)			
Specimen Number*	Strength (psi)	Modulus ($x10^{-6}$ psi)	Porosity (%)
LF 7	219	16.6	0.18
8	240	19.6	0
10	229	18.7	0
12	238	19.0	0
14	239	21.5	0
1[illegible]	256	20.1	0
17	241	20.1	0.03
Average	237	19.4	.03
Cv	4.8	7.84	- -

*Missing specimens were cut up into compression specimens.

4. SHEAR STRENGTH IN UD PANELS

1109-36 VB
1109-39 AC
1109-54 AC/ES
1109-57 AC/AP

MECHANICAL PROPERTIES
1109-36 0° 12 PLY VACUUM BAG

Specimen Number	Shear Strength (psi)	Porosity (%)	Velocity fps	Specimen Number	Shear Strength (psi)	Porosity (%)	Velocity fps
SBS 1	7140	8.70	39453	SBS 16	7000	8.52	42083
2	5930	4.35	45089	17	8970	4.44	45089
3	8040	4.66	43534	18	8650	4.85	45089
4	7340	6.46	45089	19	7170	6.26	42726
5	6810	6.75	45089	20	7350	6.30	44298
6	7030	6.32	45089	21	6700	6.77	43534
7	8190	4.82	45909	22	8200	5.40	42797
8	8210	5.22	45089	23	8060	7.92	44298
9	6080	5.93	44298	24	7890	5.94	43534
10	5860	6.30	44298	25	7430	6.00	43534
11	6220	5.42	43534	26	8400	5.50	43534
12	5820	5.45	45909	27	6880	5.79	44298
13	7800	5.48	45089	28	7820	6.02	44298
14	8580	4.46	46759	29	8070	5.16	45909
15	8100	5.45	45909	30	7990	5.16	45015
Average	7140	5.71	44675	Average	7770	6.00	44002
Cv	13.7	19.3	3.78	Cv	8.58	18.1	2.35

	Strength	Porosity	Velocity
Overall For SBS Ave =	7450	5.86	44337
Cv =	11.9	18.5	3.28

MECHANICAL PROPERTIES
1109-39 0° 12 PLY AUTOCLAVE

Specimen Number	Shear Strength (psi)	Porosity (%)	Velocity fps	Specimen Number	Shear Strength (psi)	Porosity (%)	Velocity fps
SBS 1	13,800	.14	44006	SBS 16	13,400	.39	44006
2	15,400	0	47327	17	15,300	.02	47327
3	16,300	0	46373	18	12,400	.30	47248
4	16,600	0	46373	19	13,000	.57	45530
5	16,600	0	45530	20	14,100	.68	45455
6	16,300	0	44717	21	12,700	.68	45455
7	17,000	0	46373	22	14,700	.57	47170
8	16,100	0	47248	23	13,900	.99	46296
9	16,200	.15	46373	24	11,600	1.31	43860
10	16,000	.19	47248	25	9,810	1.31	44643
11	16,500	0	46373	26	12,700	1.22	47170
12	16,500	0	46373	27	14,900	.62	45530
13	16,500	0	46373	28	12,600	.78	45530
14	16,600	0	48237	29	11,300	.75	46373
15	16,400	.11	47237	30	11,700	0	44792
Average	16,200	.04	46410	Average	12,900	.67	45759
Cv	4.64	- -	2.2	Cv	11.6	- -	2.4

	Strength	Porosity	Velocity
Overall For SBS Ave =	14,600	.36	46084
Cv =	13.8	- -	2.4

MECHANICAL PROPERTIES
1109-54 0° 12 PLY AUTOCLAVE - EXCESS SOLVENT

Specimen Number	Shear Strength (psi)	Porosity (%)	Specimen Number	Shear Strength (psi)	Porosity (%)
SBS 1	12,700	1.88	SBS 16	15,300	1.41
2	13,900	2.88	17	19,600	2.03
3	14,600	1.02	18	14,900	1.43
4	14,600	1.26	19	15,600	0.94
5	13,700	1.52	20	15,800	1.05
6	13,100	1.87	21	14,900	1.25
7	12,300	2.37	22	14,500	1.66
8	12,200	1.88	23	15,600	1.41
9	11,100	2.40	24	16,000	1.07
10	11,800	2.95	25	16,300	1.05
11	12,500	2.72	26	15,800	1.17
12	9,140	1.78	27	15,400	1.08
13	10,700	2.36	28	15,400	1.22
14	9,910	2.68	29	14,900	1.20
15	10,900	2.22	30	13,000	0.18
Average	12,200	2.11	Average	15,100	1.12
Cv	13.4	- -	Cv	6.05	- -

	Strength	Porosity
Overall For SBS Ave =	13,600	1.66
Cv =	14.4	- -

MECHANICAL PROPERTIES
1109-57 (° 12 PLY AUTOCLAVE - ADVANCED PREPREG

Specimen Number	Shear Strength (psi)	Porosity (%)	Specimen Number	Shear Strength (psi)	Porosity (%)
SBS 1	12,800	.72	SBS 16	14,200	.20
2	14,100	0	17	15,300	.12
3	13,600	0	18	15,200	.05
4	15,100	0	19	15,400	.05
5	13,200	0	20	15,400	.06
6	15,600	0	21	15,600	.13
7	15,100	.26	22	15,100	.20
8	15,200	.05	23	15,500	.12
9	15,800	.07	24	15,200	.33
10	14,900	.15	25	15,200	.14
11	15,800	.22	26	15,800	.30
12	14,300	.22	27	15,600	.30
13	16,000	.24	28	15,600	.18
14	15,400	.21	29	15,900	.19
15	14,300	.18	30	14,600	.27
Average	14,700	.12	Average	15,300	.17
Cv	6.73	- -	Cv	2.87	- -

	Strength	Porosity
Overall For SBS Average =	15,046	0.14
Cv =	5.4	- -

5. TENSILE PROPERTIES IN A 0/90 CROSS PLY LAMINATE

1109-38 VB
1109-41 AC
1109-55 AC/ES
1109-58 AC/AP

MECHANICAL PROPERTIES
PANEL 1109-38 0/90, 7 PLY VACUUM BAG - MOLDED

Specimen Number	Orientation	ULT Stress $x10^3$	E $x10^{-6}$	% Strain	.2% Yield Strength (KSI)	Porosity (%)	Velocity fps
1	90°	60.1	8.63	.74	- -	4.25	20038
2	↓	69.6	10.0	.72	- -	3.95	20313
3		79.7	9.10	.89	- -	4.34	19699
4		61.3	8.42	.74	- -	4.90	22804
5		86.0	8.45	1.04	- -	4.67	19269
6		74.5	7.96	.93	- -	5.32	18854
Average		71.9	8.59	.84		4.57	20162
Cv		14.2	10.4	15.5		- -	6.92
7	0°	72.5	9.29	.77	- -	5.46	21744
8	↓	105.0	13.2	.80	- -	3.32	23115
9		96.7	12.6	.78	- -	4.23	22560
10		81.2	11.3	.73	- -	4.92	21902
11		93.2	11.5	.82	- -	4.70	22001
12		112.0	11.8	.95	- -	4.90	22529
Average		93.4	11.6	.81		4.58	22308
Cv		15.7	11.6	9.4		- -	2.31
13	45°	17.5	2.05	1.54	13.1	4.68	
14	↓	17.7	2.11	1.45	13.3	4.70	
15		18.1	2.04	1.77	13.0	4.70	
16		18.0	2.05	1.69	12.8	4.85	
17		18.4	1.97	1.81	13.4	4.70	
18		20.2	2.16	1.96	15.2	4.50	
Average		18.3	2.06	1.70	13.4	4.68	
Cv		5.3	3.1	10.9	6.5	- -	

MECHANICAL PROPERTIES
PANEL 1109-41 0/90, 7 PLY AUTOCLAVE - MOLDED

Specimen Number	Orientation	ULT Stress $x10^3$	E $x10^{-6}$	% Strain	.2% Yield Strength (KSI)	Porosity (%)	Velocity fps	Poisson's Ratio
1	90°	81.3	8.03	1.03	- -	1.41	20804	
2	↓	91.2	10.3	.94	- -	.84	- - -	
3	↓	102.0	10.0	1.02	- -	.51	20804	
4	↓	101.0	9.76	1.08	- -	.47	19737	
5	↓	97.1	10.0	.98	- -	.31	20325	
6	↓	83.4	9.43	.89	- -	.37	18977	.028
Average		92.7	9.59	.99		.61	20129	.028
Cv								
7	0°	98.7	11.7	.87	- -	.75	22846	
8	↓	109.0	13.3	.82	- -	.30	23199	
9	↓	87.8	12.7	.69	- -	.30	23164	
10	↓	107.0	13.3	.82	- -	.22	22986	
11	↓	103.0	12.1	.88	- -	.27	22470	
12	↓	85.0	12.1	.70	- -	.19	21754	.045
Average		98.4	12.5	.80		.34	22736	.045
Cv		10.1	5.4	10.3			2.41	
13	45°	22.9	2.44	2.58	14.5	.15		
14	↓	22.5	2.31	2.14	14.2	.19		
15	↓	23.0	2.35	2.39	15.0	.19		
16	↓	22.7	2.42	2.26	15.1	.18		
17	↓	22.7	2.50	2.13	14.8	.21		
18	↓	23.5	2.30	2.46	16.0	.18		.63
Average		22.9	2.39	2.3	14.9	.18		.63
Cv		1.5	3.3	7.8	4.1			

MECHANICAL PROPERTIES
PANEL 1109-55 0/90, 7 PLY AUTOCLAVE - EXCESS SOLVENT

Specimen Number	Orientation	Strength (KSI)	Modulus (x10^{-6} psi)	Failure Strain (%)	.2% Yield Strength (KSI)	Porosity (%)	Poisson's Ratio
1	90°	64.0	9.82	.72	- -	.89	
2		73.1	9.71	.75	- -	.75	
3		75.2	9.65	.79	- -	.80	
4		55.2	9.65	.58	- -	.75	
5		75.2	9.80	.77	- -	.72	
6		80.0	9.82	.62	- -	.68	.031
Average		70.4	9.31	.71		.76	.031
Cv		13	11.9	12.0			
7	0°	91*	10.8	.87	- -	1.90	
8		110	13.1	.82	- -	1.42	
9		105	13.2	.78	- -	1.35	
10		100	13.2	.80	- -	1.17	
11		134	13.0	.89	- -	1.11	
12		98	11.8	.83	- -	1.22	.056
Average		106.0	12.5	.83		1.36	.050
Cv		14.1	7.9	5.0			
13	45°	23.0	2.42	2.52	15.8	.84	
14		23.1	2.58	2.01	15.4	.84	
15		22.7	2.45	2.08	15.5	.84	
16		22.0	2.38	2.28	15.2	.90	
17		22.7	2.35	2.52	14.8	.95	
18		22.5	2.34	2.54	14.6	.96	.69
Average		22.8	2.4	2.3	15.2	.88	.68
Cv		1.7	3.7	10.3	2.9		

*Grip Failure

MECHANICAL PROPERTIES
PANEL 1109-58 0/90, 7 PLY AUTOCLAVE - ADVANCED PREPREG

Specimen Number	Orientation	Strength (KSI)	Modulus ($x10^{-6}$ psi)	Failure Strain (%)	.2% Yield Strength (KSI)	Porosity (%)
1	90°	68.1	8.68	.81	- -	.24
2		80.0	9.62	.84	- -	.22
3		70.7	9.52	.75	- -	.22
4		82.2	9.75	.85	- -	.24
5		53.8	9.09	.59	- -	.34
6		58.8	9.88	.60	- -	.19
Average		68.9	9.42	.74		.24
Cv		16.3	4.8	15.9		21.4
7	0°	88.3**	10.9	.83	- -	.65
8		102.0	12.9	.79	- -	.37
9		95.0*	14.1	- -	- -	.25
10		75.0*	12.2	- -	- -	.34
11		104.0*	13.3	- -	- -	.30
12		90.0*	11.4	- -	- -	.49
Average		92.4	12.46	.81		.40
Cv		11.4	9.6			5.3
13	45°	25.3	2.29	2.89	15.7	.22
14		25.5	2.29	3.23	15.1	.24
15		26.1	2.39	3.32	15.4	.21
16		25.1	2.38	2.83	16.4	.19
17		26.0	2.45	4.06	13.8	.19
18		25.5	2.33	2.55	- -	.21
Average		25.6	2.36	3.15	15.2	.21
Cv		1.5	2.6	16.7	6.3	9.0

*Tab failed at these strength levels.
**Failed at extensometer points.

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13. ABSTRACT

Porosity has been artifically introduced in graphite/epoxy laminates by either varying the volitale content of the prepreg or by altering the pressure during curing. A series of techniques was used to determine the resulting porosity and establish the variability within a panel. These tecnniques included direct and indirect measures of the void content and were compared to standard non-destructive techniques for porosity detection.

Tensile, compressive, shear and flexure properties were obtained on unidirectional and cross plied specimens. The properties showed varying sensitivity to porosity, the horizontal shear strength being the most severely degraded of those properties measured.

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